

TPS61378-Q1 25- μ A Quiescent Current Synchronous Boost Converter with Load Disconnect

1 Features

- AEC-Q100 qualified for automotive applications
 - Device temperature grade 1: -40°C to 125°C ambient operating temperature range
- TPS61378-Q1 Wettable Flank
- TPS61378L-Q1 Immersion Sn
 - Provides shorter production cycle time and longer shelf life
- Function Safety-Capable
 - Documentation available to aid functional safety system design
- Flexible input and output operation range
 - Input voltage range: 2.3V to 14V
 - Programmable output voltage : 4.0V to 18.5V
 - Input voltage range: 2.3V to 14V
 - Fixed output options: 5V, 5.25V, and 5.5V
 - Programmable peak current limit: 1A to 4.8A
- Avoid AM band interference and crosstalk
 - Dynamically programmable switching frequency: 200kHz to 2.2MHz
 - Spread spectrum frequency modulation at FPWM mode
 - Optional clock synchronization
- Minimize solution size for space constraint applications
 - Integrated LS/HS/ISO FET: $R_{DS(ON)}$ 50m Ω /50m Ω /100m Ω
 - Support up to 2.2MHz with small L-C
- Minimized light load and idle state current consumption
 - 25 μ A quiescent current into VIN pin
 - 0.5 μ A shutdown current into VIN pin
 - Selectable auto PFM and forced PWM mode
 - True load disconnect during shutdown or fault conditions
- Integrated protection features
 - Supports VIN close to VOUT operation
 - Input undervoltage lockout and output overvoltage protection
 - Hiccup output short circuit protection
 - Power good indicator
 - Thermal shutdown protection at 165°C
- Higher than 90% efficiency under 0.8A load from 3.3V to 9V conversion

2 Applications

- Advanced driver-assistance system (ADAS)
- Automotive infotainment and cluster
- Body electronics and lighting

- Emergency call (eCall)

3 Description

The TPS61378-Q1 is a fully-integrated synchronous boost converter with an integrated load disconnect function. The input voltage covers 2.3V to 14V while the maximal output voltage covers up to 18.5V. The switching current limit is programmable from 1A to 4.8A. The device consumes 25 μ A quiescent current from V_{IN} .

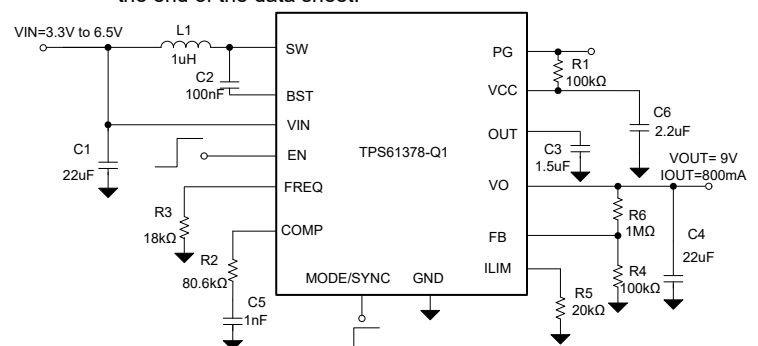
The TPS61378-Q1 employs peak current mode control with the switching frequency programmable from 200kHz to 2.2MHz. The device works in fixed frequency PWM operation in medium to heavy loads. There are two optional modes in light load by configuring the MODE pin: auto PFM mode and forced PWM to balance the efficiency and noise immunity in light load. The switching frequency can be synchronized to an external clock. The TPS61378-Q1 uses the spread spectrum of the internal clock to be more EMI friendly at FPWM mode. In addition, there is an internal soft-start time to limit the inrush current.

The TPS61378-Q1 has various fixed output voltage versions to save the external feedback resistor. It supports the external loop compensation so that the stability and transient response can be optimized at wider V_{OUT}/V_{IN} ranges. It also integrates robust protection features including output short protection, output overvoltage protection, and thermal shutdown protection. The TPS61378-Q1 is available in a 3mm $\times$ 3mm 16-pin QFN package with wettable flank.

Device Information

PART NUMBER	PACKAGE ⁽¹⁾	BODY SIZE (NOM)
TPS61378-Q1	WQFN-16	3.0mm $\times$ 3.0mm

- (1) For all available packages, see the orderable addendum at the end of the data sheet.



Typical Application



Table of Contents

1 Features	1	8 Application and Implementation	17
2 Applications	1	8.1 Application Information.....	17
3 Description	1	8.2 Typical Application.....	17
4 Device Comparison Table	3	9 Power Supply Recommendations	26
5 Pin Configuration and Functions	4	10 Layout	27
6 Specifications	5	10.1 Layout Guidelines.....	27
6.1 Absolute Maximum Ratings.....	5	10.2 Layout Example.....	27
6.2 ESD Ratings	5	11 Device and Documentation Support	28
6.3 Recommended Operating Conditions.....	5	11.1 Device Support.....	28
6.4 Thermal Information.....	5	11.2 Receiving Notification of Documentation Updates..	28
6.5 Electrical Characteristics.....	6	11.3 Support Resources.....	28
6.6 Typical Characteristics.....	8	11.4 Trademarks.....	28
7 Detailed Description	11	11.5 Glossary.....	28
7.1 Overview.....	11	11.6 Electrostatic Discharge Caution.....	28
7.2 Functional Block Diagram.....	12	12 Revision History	28
7.3 Feature Description.....	12	13 Mechanical, Packaging, and Orderable Information	29
7.4 Device Functional Modes.....	15		

4 Device Comparison Table

PART NUMBER	OUTPUT VOLTAGE (V)	OUTPUT VOLTAGE SELECTION RESISTOR (R_{FB}) ⁽²⁾	SPREAD SPECTRUM
TPS61378-Q1	5	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Enable
	5.25	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	5.5	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	Adjustable	$R_{FB} \geq 14.4\text{ k}\Omega$	
TPS613781-Q1 ⁽¹⁾	5.7	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Enable
	6.2	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	7	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	8	$R_{FB} \geq 14.4\text{ k}\Omega$	
TPS613782-Q1 ⁽¹⁾	9	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Enable
	10	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	11	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	12	$R_{FB} \geq 14.4\text{ k}\Omega$	
TPS613783-Q1	5	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Disable
	5.25	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	5.5	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	Adjustable	$R_{FB} \geq 14.4\text{ k}\Omega$	
TPS613784-Q1 ⁽¹⁾	5.7	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Disable
	6.2	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	7	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	8	$R_{FB} \geq 14.4\text{ k}\Omega$	
TPS613785-Q1	9	$0\Omega \leq R_{FB} \leq 2.4\text{ k}\Omega$	Disable
	10	$3.6\text{ k}\Omega \leq R_{FB} \leq 4.8\text{ k}\Omega$	
	11	$7.2\text{ k}\Omega \leq R_{FB} \leq 9.6\text{ k}\Omega$	
	12	$R_{FB} \geq 14.4\text{ k}\Omega$	

(1) Product Preview. Contact TI factory for more information.

(2) R_{FB} is the sensed resistor from FB pin. Please refer to [Section 8.2.2.1](#) for details. Avoid using resistors other than the recommended values, otherwise the output voltage value cannot be guaranteed.

5 Pin Configuration and Functions

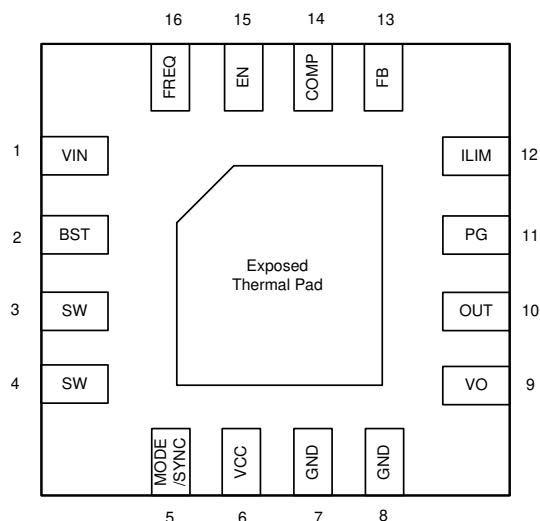


Figure 5-1. 16-Pin WQFN RTE Package (Transparent Top View)

Table 5-1. Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
VIN	1	I	IC power supply input
BST	2	I	Power supply for high-side N-MOSFET gate drivers. A capacitor must be connected between this pin and the SW pin.
SW	3, 4	PWR	The switching node pin of the converter. It is connected to the drain of the internal low-side FET and the source of the high-side FET.
MODE/SYNC	5	I	Mode selection pin. MODE = high, forced PWM mode MODE = low or floating, auto PFM mode This pin can also be used to synchronize the external clock. Refer to Table 7-2 for details.
VCC	6	O	Output of internal regulator. A ceramic capacitor with more than 1 μ F must be connected between this pin and GND.
GND	7, 8	PWR	Power ground of the IC. It is connected to the source of the low-side FET.
VO	9	PWR	Output of the isolation FET. Connect load to this pin to achieve input/output isolation.
OUT	10	PWR	Output of the drain of the HS FET. Connect this pin because the output can disable the load disconnect/short protection feature (or short this pin with the VO pin).
PG	11	O	Power good indicator and open drain output
ILIM	12	I	Current limit setting pin. Use a resistor to set the desired peak current limit. Refer to Section 7.3.7 for details.
FB	13	I	Feedback pin. Use a resistor divider to set the desired output voltage. Refer to Section 8.2.2.1 for details.
COMP	14	I	Output of the internal transconductance error amplifier. An external RC network is connected to this pin to optimize the loop stability and response time.
EN	15	I	Enable logic input
FREQ	16	I	Frequency setting pin. Connect a resistor between this pin and GND pin to set the desired frequency.
Thermal Pad	-	-	The thermal pad must be connected to the power ground plane for good power dissipation.

6 Specifications

6.1 Absolute Maximum Ratings

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

		MIN	MAX	UNIT
Voltage range at terminals ⁽²⁾	VIN	-0.3	16	V
	VO, SW, OUT	-0.3	23	V
	BST	-0.3	SW + 6	V
	MODE/SYNC, FB, FREQ, ILIM, VCC, COMP, EN	-0.3	6	V
	PG	-0.3	20	V
T _J ⁽³⁾	Operating junction temperature	-40	150	°C
T _{stg}	Storage temperature	-65	150	°C

- (1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) All voltage values are with respect to network ground terminal.
- (3) High junction temperatures degrade operating lifetime. Operating lifetime is de-rated for junction temperatures greater than 125°C

6.2 ESD Ratings

			VALUE	UNIT
V _(ESD) ⁽¹⁾	Electrostatic discharge	Human-body model (HBM), per AEC Q100-002 ⁽²⁾	±2000	V
		Charged-device model (CDM), per AEC Q100-011, all pins ⁽³⁾	±500	
V _(ESD) ⁽¹⁾	Electrostatic discharge	Charged-device model (CDM), per AEC Q100-011, corner pins (1,4,5,8,9,12,13,16) ⁽³⁾	±750	V

- (1) Electrostatic discharge (ESD) to measure device sensitivity and immunity to damage caused by assembly line electrostatic discharges in to the device.
- (2) Level listed above is the passing level per ANSI, ESDA, and JEDEC JS-001. JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process. Manufacturing with less than 500-V HBM is possible with the necessary precautions.
- (3) Level listed above is the passing level per EIA-JEDEC JESD22-C101. JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process. Manufacturing with less than 250-V CDM is possible with the necessary precautions.

6.3 Recommended Operating Conditions

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

		MIN	NOM	MAX	UNIT
V _{IN}	Input voltage	2.3		14	V
V _{OUT}	Output voltage	4		18.5	V
T _J	Operating junction temperature ⁽¹⁾	-40		150	°C

- (1) High junction temperatures degrade operating lifetimes. Operating lifetime is de-rated for junction temperatures greater than 125°C.

6.4 Thermal Information

THERMAL METRIC ⁽¹⁾		TPS61378-Q1	UNIT
		RTE	
		16 PINS	
R _{θJA}	Junction-to-ambient thermal resistance	46.2	°C/W
R _{θJC(top)}	Junction-to-case (top) thermal resistance	43.5	°C/W
R _{θJB}	Junction-to-board thermal resistance	18.5	°C/W
ψ _{JT}	Junction-to-top characterization parameter	1.1	°C/W
ψ _{JB}	Junction-to-board characterization parameter	18.5	°C/W
R _{θJC(bot)}	Junction-to-case (bottom) thermal resistance	8.8	°C/W

- (1) For more information about traditional and new thermal metrics, see the [Semiconductor and IC Package Thermal Metrics](#) application report .

6.5 Electrical Characteristics

$T_J = -40$ to 125°C , $L = 1\ \mu\text{H}$, $V_{IN} = 3.3\ \text{V}$ and $V_{OUT} = 9\ \text{V}$ (VO pin). Typical values are at $T_J = 25^\circ\text{C}$, (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
POWER SUPPLY						
V_{IN}	Input voltage range		2.3		14	V
V_{IN_UVLO}	VIN under voltage lockout threshold	V_{IN} rising		2.2	2.3	V
		V_{IN} falling		2.04	2.2	V
V_{IN_HYS}	VIN UVLO hysteresis			160		mV
V_{CC_UVLO}	VCC UVLO threshold	V_{CC} rising		2.2		V
V_{CC_HYS}	VCC UVLO hysteresis	V_{CC} hysteresis		150		mV
V_{CC}	VCC regulation	$I_{VCC} = 6\ \text{mA}$, $V_{OUT} = 9\text{V}$		4.8		V
I_Q	Quiescent current into V_{IN} pin	IC enabled, no load, $V_{IN} = 3.3\ \text{V}$, $V_{OUT} = 18.5\ \text{V}$, $V_{FB} = V_{REF} + 0.1\ \text{V}$,		25	35	μA
I_Q	Quiescent current into OUT pin	IC enabled, no load, $V_{IN} = 3.3\ \text{V}$, $V_{OUT} = 18.5\ \text{V}$, $V_{FB} = V_{REF} + 0.1\ \text{V}$,		10	20	μA
I_{SD}	Shutdown current into VIN pin	IC disabled, $V_{IN} = 14\ \text{V}$, $\text{EN} = \text{GND}$		0.6	5	μA
I_{SW_LKG}	Leakage current into SW	IC disabled, $V_{IN} = \text{OUT} = \text{SW} = 14\ \text{V}$			5	μA
I_{VO_LKG}	Reverse leakage current into VO	IC disabled, $\text{OUT} = \text{VO} = 5\ \text{V}$, $\text{SW} = 0$			5	μA
OUTPUT VOLTAGE						
V_{OVP}	Output over-voltage protection threshold	$V_{IN} = 3.3\ \text{V}$, V_{OUT} rising	19.3	20	20.5	V
V_{OVP_HYS}	Output over-voltage protection hysteresis	$V_{IN} = 3.3\ \text{V}$, OVP threshold		0.5		V
VOLTAGE REFERENCE						
V_{REF}	Reference Voltage at FB pin	$T_J = -40$ to 125°C , $R_{FB} = 16.0\ \text{k}\Omega$	0.788	0.800	0.812	V
V_{OUT_5V}		$T_J = -40$ to 125°C , $R_{FB} = 2.0\ \text{k}\Omega$	4.85	5.00	5.15	V
$V_{OUT_5.25V}$		$T_J = -40$ to 125°C , $R_{FB} = 4.0\ \text{k}\Omega$	5.10	5.25	5.35	V
$V_{OUT_5.5V}$		$T_J = -40$ to 125°C , $R_{FB} = 8.0\ \text{k}\Omega$	5.35	5.50	5.65	V
V_{OUT_5V}		TPS613783Q1, $T_J = -40$ to 125°C , $R_{FB} = 2.0\ \text{k}\Omega$	4.85	5.00	5.15	V
$V_{OUT_5.25V}$		TPS613783Q1, $T_J = -40$ to 125°C , $R_{FB} = 4.0\ \text{k}\Omega$	5.10	5.25	5.35	V
$V_{OUT_5.5V}$		TPS613783Q1, $T_J = -40$ to 125°C , $R_{FB} = 8.0\ \text{k}\Omega$	5.35	5.50	5.65	V
V_{OUT_9V}		TPS613785Q1, $T_J = -40$ to 125°C , $R_{FB} = 2.0\ \text{k}\Omega$	8.75	9.00	9.15	V
V_{OUT_10V}		TPS613785Q1, $T_J = -40$ to 125°C , $R_{FB} = 4.0\ \text{k}\Omega$	9.75	10.00	10.20	V
V_{OUT_11V}		TPS613785Q1, $T_J = -40$ to 125°C , $R_{FB} = 8.0\ \text{k}\Omega$	10.70	11.00	11.20	V
V_{OUT_12V}		TPS613785Q1, $T_J = -40$ to 125°C , $R_{FB} = 16.0\ \text{k}\Omega$	11.70	12.00	12.22	V
I_{FB_LKG}	Leakage current into FB pin				50	nA
POWER SWITCH						
$R_{DS(on)}$	Low-side MOSFET on resistance	$V_{CC} = 4.85\ \text{V}$		50		m Ω
$R_{DS(on)}$	High-side MOSFET on resistance	$V_{CC} = 4.85\ \text{V}$		50		m Ω
$R_{DS(on)}$	Isolation MOSFET on resistance	$V_{CC} = 4.85\ \text{V}$		100		m Ω
CURRENT LIMIT						
I_{LIM_SW}	Peak switching current limit FPWM	$R_{LIM} = 20\ \text{k}\Omega$, Duty cycle = 65%	4	4.8	5.55	A
I_{LIM_SW}	Peak switching current limit Auto PFM	$R_{LIM} = 20\ \text{k}\Omega$, Duty cycle = 65%	4	4.8	5.55	A
I_{LIM_SW}	Peak switching current limit FPWM	$R_{LIM} = 102\ \text{k}\Omega$, Duty cycle = 65%, 4.7 μH		0.75		A
I_{LIM_SW}	Peak switching current limit Auto PFM	$R_{LIM} = 102\ \text{k}\Omega$, Duty cycle = 65%, 4.7 μH		0.75		A
$I_{LIM_SS_1}$	Peak switching current limit at softstart	$V_{IN} = 3.3\ \text{V}$, $V_{OUT} = 0\ \text{V}$, $R_{LIM} = 20\ \text{k}\Omega$	0.9	1.15	1.4	A
SWITCHING FREQUENCY						
F_{sw}	Switching frequency	$R_{FREQ} = 18\ \text{k}\Omega$	2050	2200	2400	kHz

$T_J = -40$ to 125°C , $L = 1\ \mu\text{H}$, $V_{IN} = 3.3\ \text{V}$ and $V_{OUT} = 9\ \text{V}$ (VO pin). Typical values are at $T_J = 25^\circ\text{C}$, (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
F _{sw}	Switching frequency	R _{FREQ} = 218 k Ω	180	200	230	kHz
D _{max}	Maximum Duty Cycle	R _{FREQ} = 18 k Ω	78			%
t _{ON_min}	Minimal on time			70		ns
F _{DITHER}				10%		F _{sw}
F _{pattern}				0.4%		F _{sw}
ERROR AMPLIFIER						
I _{SINK}	COMP pin sink current	V _{FB} = V _{REF} + 0.2V		6		μA
I _{SOURCE}	COMP pin source current	V _{FB} = V _{REF} - 0.2V		6		μA
V _{CCLPH}	COMP pin high clamp voltage	V _{FB} = V _{REF} - 0.2V, I _{LIM} = 4.8 A		1.3		V
V _{CCLPL}	COMP pin high low voltage	V _{FB} = V _{REF} + 0.2V,		0.6		V
G _{mEA}	Error amplifier trans conductance	V _{COMP} = 1.0 V		70		μS
POWER GOOD						
V _{PG_TH}	PG threshold for rising FB voltage	Reference to V _{REF}		90%		
V _{PG_HYS}	PG hysteresis	Reference to V _{REF}		5%		
I _{PG_SINK}	PG pin sink current capability	V _{PG} = 0.4 V		20		mA
t _{PG_DELAY}	PG delay time		2.5	3.4	4.3	ms
DOWN MODE						
t _{EN_DELAY}	Delay time between EN high and device working			0.4		ms
t _{SS}	Softstart time			2.5		ms
t _{HCP_ON}	Hiccup on time			1.8		ms
t _{HCP_OFF}	Hiccup off time			67		ms
SYNC TIMING						
f _{SYNC_MIN}				200		kHz
f _{SYNC_MAX}				2200		kHz
EN/SYNC LOGIC						
V _{IH}	EN, MODE/SYNC pins Logic high threshold			1.2		V
V _{IL}	EN, MODE/SYNC pins Logic Low threshold		0.4			V
R _{DOWN}	EN, MODE/SYNC pins internal pull down resistor			800		k Ω
THERMAL SHUTDOWN						
t _{SD_R}	Thermal shutdown rising threshold	T _J rising		165		$^\circ\text{C}$
t _{SD_F}	Thermal shutdown falling threshold	T _J falling		145		$^\circ\text{C}$

6.6 Typical Characteristics

$V_{IN} = 3.3\text{ V}$, $V_{OUT} = 9\text{ V}$ (VO pin), $T_A = 25^\circ\text{C}$, $F_{sw} = 2.2\text{ MHz}$, unless otherwise noted.

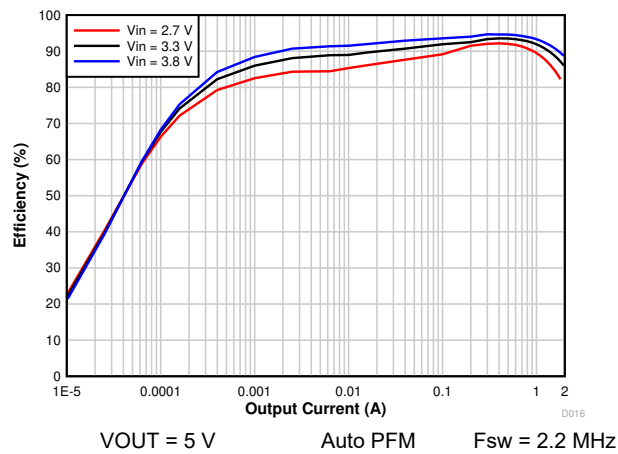


Figure 6-1. 5 V_{OUT} Efficiency vs Output Current

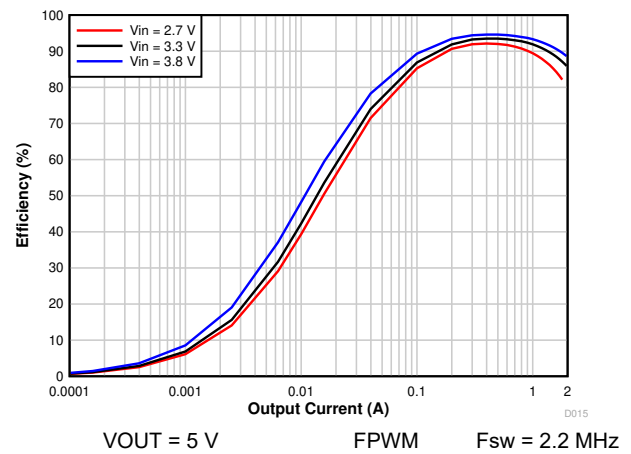


Figure 6-2. 5 V_{OUT} Efficiency vs Output Current

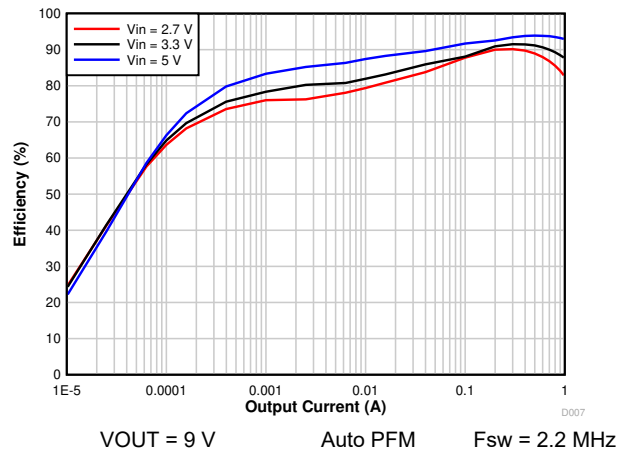


Figure 6-3. 9 V_{OUT} Efficiency vs Output Current

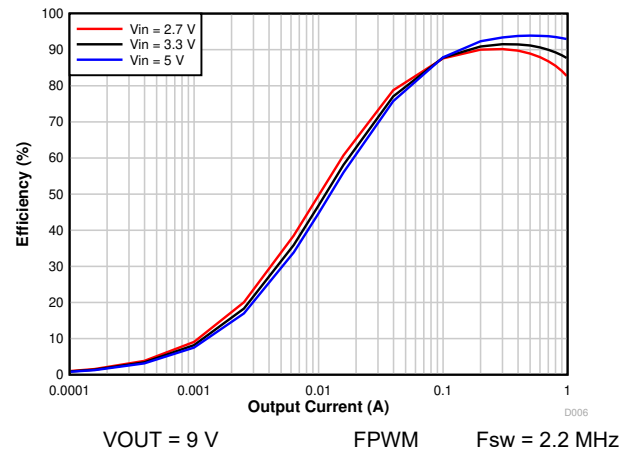


Figure 6-4. 9 V_{OUT} Efficiency vs Output Current

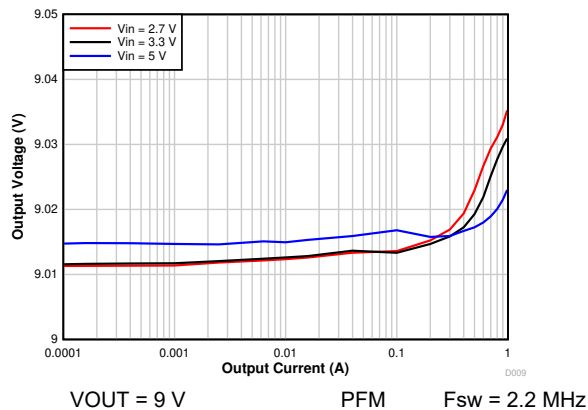


Figure 6-5. 9 V_{OUT} Regulation vs Output Current

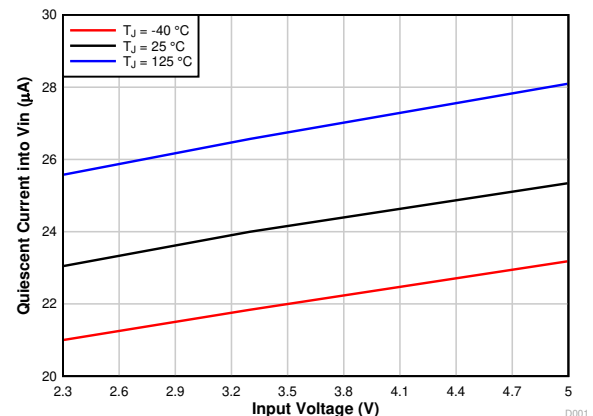


Figure 6-6. Quiescent Current into V_{IN} vs Input Voltage

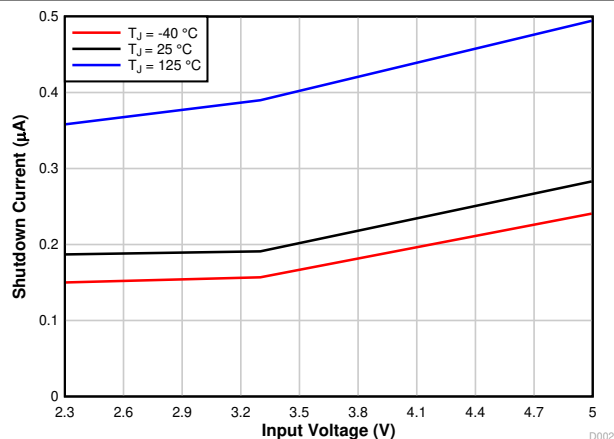


Figure 6-7. Shutdown Current vs Input Voltage

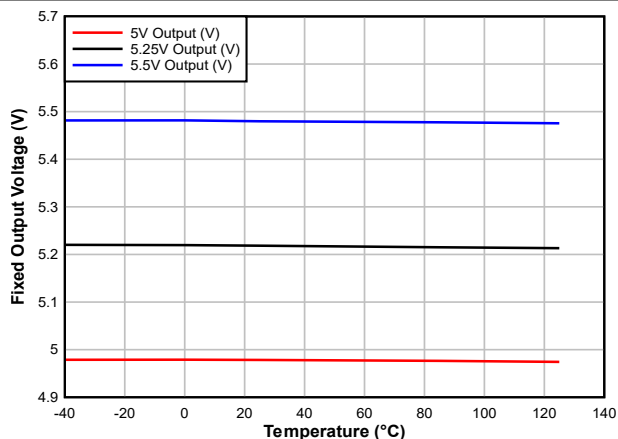


Figure 6-8. Fixed Output Voltage vs Temperature

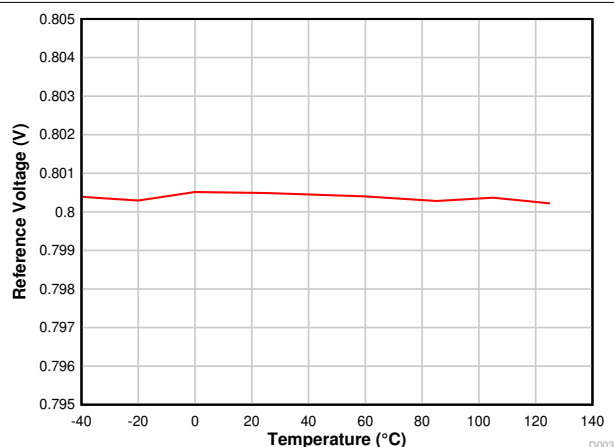


Figure 6-9. Reference Voltage vs Temperature

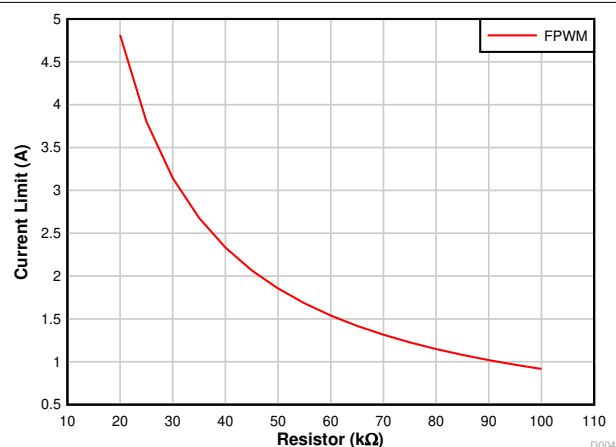


Figure 6-10. Current Limit vs Setting Resistance

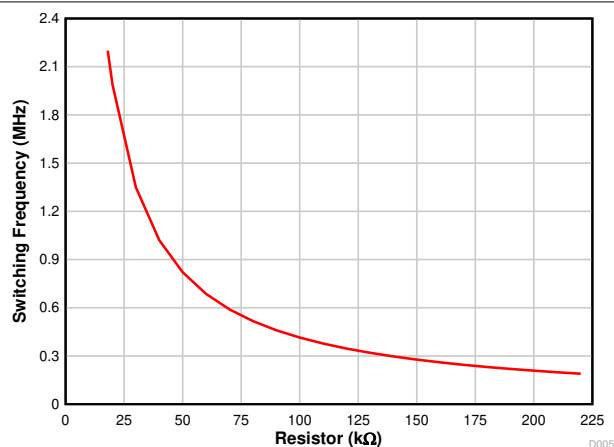


Figure 6-11. Switching Frequency vs Setting Resistance

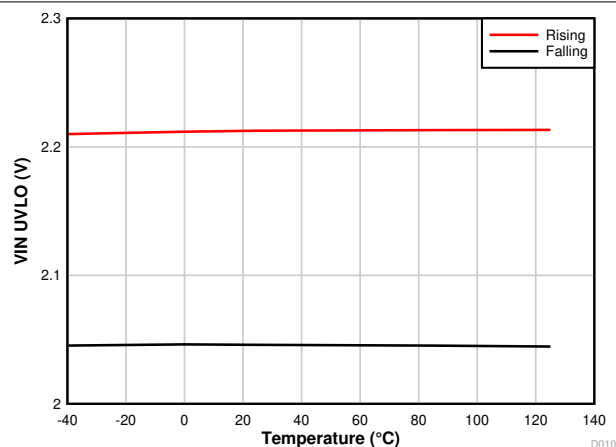


Figure 6-12. V_{IN} UVLO Threshold Voltage vs Temperature

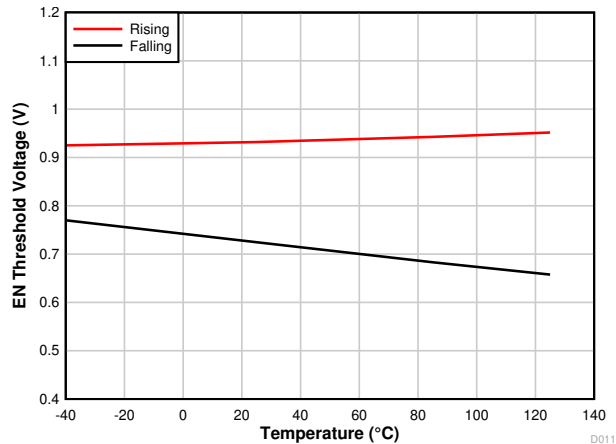


Figure 6-13. EN Threshold Voltage vs Temperature

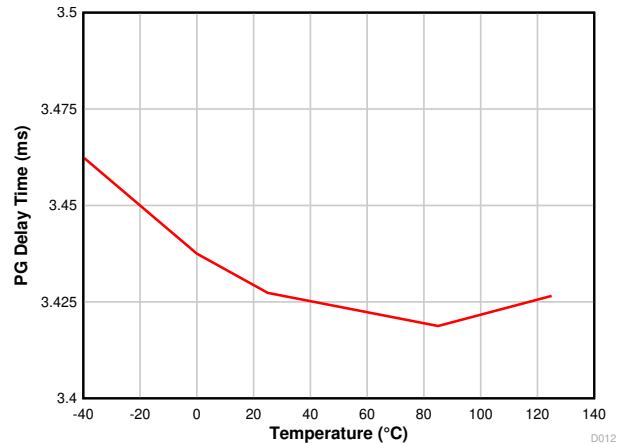


Figure 6-14. PG Delay Time vs Temperature

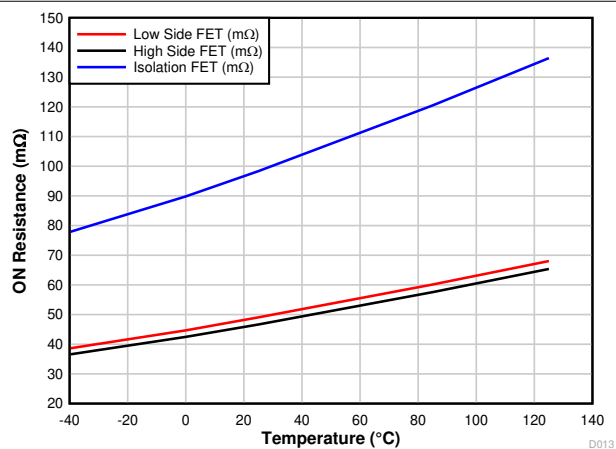
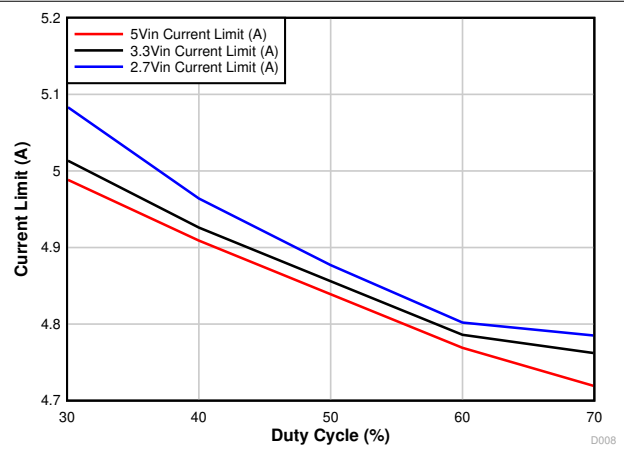
Figure 6-15. $R_{DS(on)}$ vs Temperature

Figure 6-16. Duty Cycle vs Current Limit

7 Detailed Description

7.1 Overview

The TPS61378-Q1 is a fully-integrated synchronous boost converter with load disconnect function. It supports output voltage up to 18.5 V with a maximum of a 4.8-A programmable switching peak current limit. The input voltage ranges from 2.3 V to 14 V while consuming 25- μ A quiescent current.

The TPS61378-Q1 utilizes the fixed-frequency peak current control scheme, which has an internal oscillator and supports adjustable switching frequency from 200 kHz to 2.2 MHz.

The TPS61378-Q1 operates with fixed-frequency pulse width modulation (PWM) from medium to heavy load. At the beginning of each switching cycle, the low-side N-MOSFET switch is turned on. The inductor current ramps up to a peak current that is determined by the output of the internal error amplifier (EA). Once the switching peak current triggers the output of the EA, the low-side N-MOSFET is turned off and the high-side N-MOSFET is turned on after a short dead time. The high-side N-MOSFET switch is not turned off until the next cycle as determined by the internal oscillator. The low-side switch turns on again after a short dead time and the switching cycle is repeated.

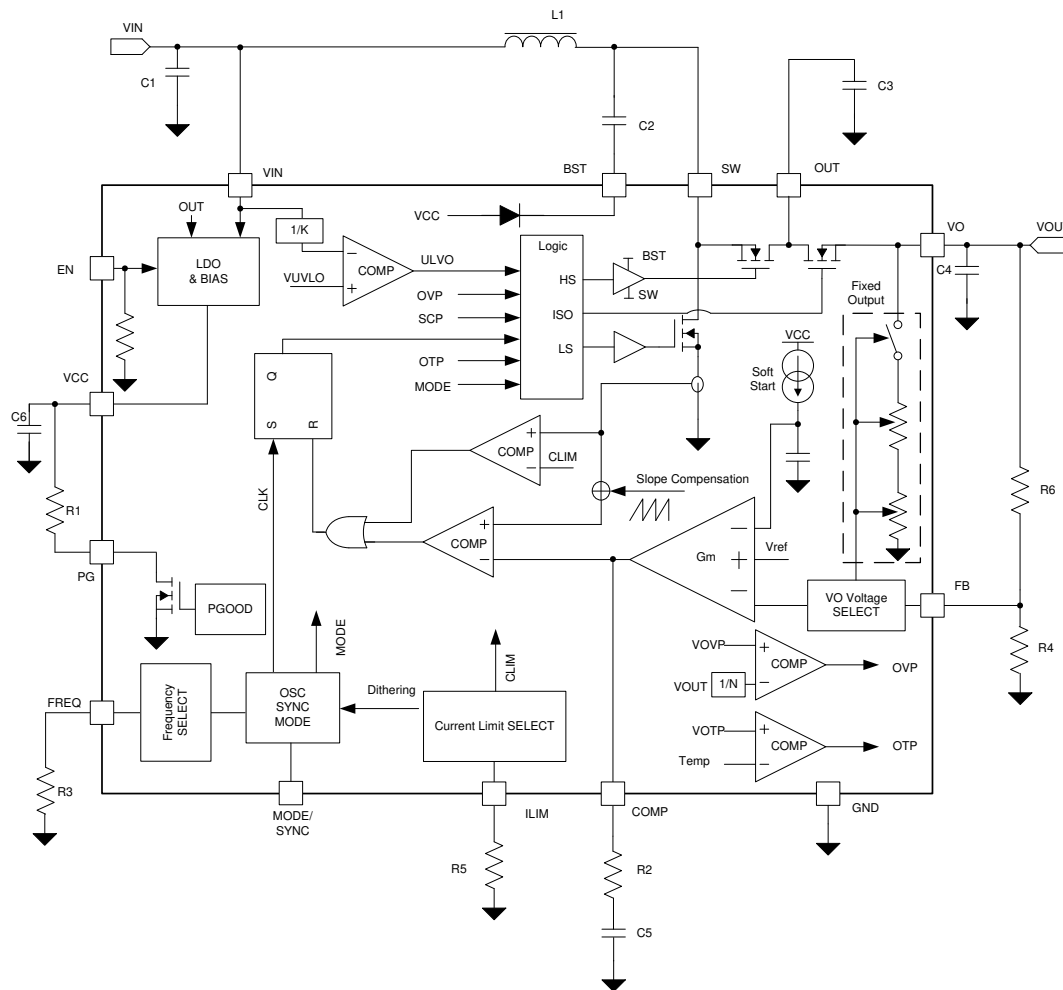
The TPS61378-Q1 provides either auto PFM or forced PWM for the light load operation by configuring the MODE/SYNC pin. In forced PWM mode, the switching frequency remains constant across the entire load range, which helps avoid frequency variation with load. The internal oscillator can be synchronized to an external clock applied on the MODE/SYNC pin. Spread spectrum modulation of the frequency in forced PWM mode helps optimize the EMI performance for automotive applications. In auto PFM mode, the switching frequency can decrease, resulting in higher efficiency.

The TPS61378-Q1 implements a cycle-by-cycle current limit to protect the device from overload during the boost operation phase. If the output current further increases and triggers the output voltage to fall below the input voltage, the TPS61378-Q1 enters into hiccup mode short protection.

There is a built-in soft-start time, which prevents the inrush current during the start-up. The TPS61378-Q1 also provides a power good (PG) indicator to enable the power sequence control for start-up.

The TPS61378-Q1 also has a number of protection features including output short protection, output overvoltage protection (OVP), and thermal shutdown protection (OTP).

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 VCC Power Supply

The internal LDO in the TPS61378-Q1 outputs a regulated voltage of 4.8 V with 10-mA output current capability. A ceramic capacitor is connected between the VCC pin and GND pin to stabilize the VCC voltage and also decouple the noise on the VCC pin. The value of this ceramic capacitor should be above 1 μ F. A ceramic capacitor with an X7R or X5R grade dielectric with a voltage rating higher than 10 V is recommended.

7.3.2 Input Undervoltage Lockout (UVLO)

An undervoltage lockout (UVLO) circuit stops the operation of the converter when the input voltage drops below the UVLO threshold of 2.04 V (typical). A hysteresis of 160 mV (typical) is added so that the device cannot be enabled again until the input voltage exceeds 2.2 V (typical). This function is implemented to prevent the device from malfunctioning when the input voltage is between 2.04 V and 2.2 V.

7.3.3 Enable and Soft Start

When the input voltage is above the UVLO threshold and the EN pin is pulled above 1.2 V, the TPS61378-Q1 is enabled. The device starts to monitor the FB pin. With a typical 400- μ s delay time after EN is pulled high, the TPS61378-Q1 starts switching. There is an internal built-in start-up time, typically 2.5 ms, to limit the inrush current during start-up.

7.3.4 Shut Down

When the input voltage is below the UVLO threshold or the EN pin is pulled low, The TPS61378-Q1 is in shutdown mode and all the functions are disabled. The input voltage is isolated from the output to minimize the leakage currents.

7.3.5 Switching Frequency Setting

The TPS61378-Q1 uses a fixed-frequency control scheme. The switching frequency can be programmed between 200kHz and 2.2MHz using a resistor from the FREQ pin to GND. The resistor must be connected when the oscillator is synchronized by external clock. The resistance is defined by [Equation 1](#).

$$F_{SW}(MHz) = \frac{41.9}{R_{FREQ}(k\Omega) + 1.05} \quad (1)$$

where

- R_{FREQ} is the resistance between the FREQ pin and the GND pin

For example, the switching frequency is 2.2 MHz if the resistance between FREQ pin and GND is 18kΩ. This pin cannot be left floating or tied to VCC.

7.3.6 Spread Spectrum Frequency Modulation

The TPS61378-Q1 uses a triangle waveform to spread the switching frequency with $\pm 10\%$ of normal frequency. The frequency of the triangle waveform is typically 0.4% of the switching frequency. For example, if the normal switching frequency of the TPS61378-Q1 is programmed to 2.2MHz, the spread spectrum function modulates the switching frequency in the range of 1.98MHz to 2.42MHz in a triangle behavior with an 8.8kHz rate.

The spread spectrum is only available while the clock of the TPS61378-Q1 is free running at its natural frequency in FPWM mode. Any of the following conditions overrides spread spectrum, turning it off:

- An external clock is applied to the MODE/SYNC pin.
- The MODE/SYNC pin is configured to be logic low or floating.

7.3.7 Adjustable Peak Current Limit

The TPS61378-Q1 adopts a cycle-by-cycle peak current limit internally and changes its current limit with different working conditions. The low-side switch is turned off immediately as soon as the switch peak current triggers the peak current limit. The peak switch current limit can be set by a resistor from the ILIM pin to ground. The relationship between the peak current limit and the resistor is shown in [Equation 2](#).

$$R_{LIM}(k\Omega) = 1.184 + \frac{90.56}{I_{LIM}(A)} \quad (2)$$

where

- R_{LIM} is the resistance between the ILIM pin and the GND. This pin cannot be left floating or connected to VCC.
- I_{LIM} is switch peak current limit

For instance, the current limit is set to 4.8 A if the R_{LIM} is 20 kΩ.

[Table 7-1](#) summarizes the peak current limit under various conditions. The current limit applies to the start-up phase.

Table 7-1. Switch Peak Current Limit

Behavior	Switch Peak Current Limit
$V_{in} < V_O$ (Not in Down Mode)	$I_{LIM}^{(1)}$
$V_{in} < V_O$ (In Down Mode)	$2/3 I_{LIM}$
$3V > V_{in} - V_O > 0V$	$4/9 I_{LIM}$
$6V > V_{in} - V_O > 3V$	$1/4 I_{LIM}$

Table 7-1. Switch Peak Current Limit (continued)

Behavior	Switch Peak Current Limit
$V_{in} - V_O > 6V$	$1/4 I_{LIM}$ & Fsw Clamp to 1.1MHz if FREQ pin setting is $> 1.1MHz$
$FB \leq 0.1V$	$1/5 I_{LIM}$ & Fsw Clamp to 1.1MHz if FREQ pin setting is $> 1.1MHz$

(1) I_{LIM} is switch peak current limit programmed in [Equation 2](#).

7.3.8 Bootstrap

The TPS61378-Q1 has an integrated bootstrap regulator circuit. A small ceramic capacitor is needed between the BST pin and SW pin to provide the gate drive supply voltage for high-side switches. The bootstrap capacitor is charged during the time when the low-side switch is in the ON state. The value of this ceramic capacitor should be above 0.1 μF . A ceramic capacitor with an X7R or X5R grade dielectric with a voltage rating higher than 6.3 V is recommended.

7.3.9 Load Disconnect

The TPS61378-Q1 integrates a load disconnect function when the input source is DC, completely cutting off the path between the input side and output side during shutdown.

The output disconnect function also allows the output short protection and minimizes the inrush current at start-up.

7.3.10 MODE/SYNC Configuration

[Table 7-2](#) summarizes the MODE/SYNC function and the entry condition.

Table 7-2. MODE/SYNC Configuration

MODE/SYNC PIN CONFIGURATION	MODE
Logic Low or Floating	Auto PFM Mode
Logic High	Forced PWM Mode
External Synchronization	Forced PWM Mode

The TPS61378-Q1 can be synchronized to an external clock applied to the MODE/SYNC pin.

7.3.11 Overvoltage Protection (OVP)

If the output voltage exceeds the OVP threshold (typically 20 V), the TPS61378-Q1 immediately stops switching until the output voltage drops below the recovery threshold (typically 19.5 V). This function protects the device against excessive voltage.

7.3.12 Output Short Protection/Hiccup

In addition to the cycle-by-cycle current limit function, the TPS61378-Q1 also has output short protection.

During normal working condition, when output draws an excessive amount of current, causing the low-side FET to reach peak current limit and the output voltage is pulled below the input voltage, the device enters short circuit protection mode, triggering the hiccup timer. When the hiccup timer is active, the device limits the current for 1.8 ms and then shuts down. After 67 ms, it restarts.

During start-up, whether normal start-up or hiccup restart, the device can trigger short protection. The device has limited loading capacity at start up phase because of smaller peak current limit, which is list in [Table 7-1](#).

Starting up with heavy load or very large capacitors at output side may causes short hiccup protection.

7.3.13 Power-Good Indicator

The TPS61378-Q1 integrates a power-good function. The power-good output consists of an open-drain NMOS, requiring an external pullup resistor connect to a suitable voltage supply like VCC. The PG pin goes high with a typical 3.4-ms delay time after VOUT reaches 90% of the target output voltage. When the output voltage drops below 85% of the target output voltage, the PG pin immediately goes low without delay.

7.3.14 Thermal Shutdown

A thermal shutdown is implemented to prevent damage due to excessive heat and power dissipation. Typically, the thermal shutdown occurs at junction temperatures exceeding 165°C. When the thermal shutdown is triggered, the device stops switching and recovers when the junction temperature falls below 145°C (typical).

7.4 Device Functional Modes

7.4.1 Forced PWM Mode

The TPS61378-Q1 enters forced PWM mode by pulling the MODE/SYNC pin to logic high for more than five switching cycles. In forced PWM mode, the TPS61378-Q1 keeps the switching frequency constant at light load condition. When the load current decreases, the output of the internal error amplifier also decreases to keep the inductor peak current down. When the output current decreases further, the high-side switch is not turned off even if the current of the high-side switch goes negative to keep the frequency constant.

7.4.2 Auto PFM Mode

The TPS61378-Q1 enters auto PFM Mode by pulling the MODE/SYNC pin to logic low for more than five switching cycles or leaving the pin floating. The TPS61378-Q1 improves the efficiency at light load when operating in PFM mode. When the output current decreases to a certain level, the output voltage of the error amplifier is clamped by the internal circuit. If the output current reduces further, the inductor current through the high-side switch will be clamped but not lowered further. Pulses are skipped to improve the efficiency at light load.

7.4.3 External Clock Synchronization

The TPS61378-Q1 supports external clock synchronization with a range of 200 kHz to 2.2 MHz. The external clock needs to be within $\pm 20\%$ of the setting frequency to ensure a reliable synchronization. The TPS61378-Q1 remains in forced PWM mode and operates in CCM across the entire load range if the oscillator is synchronized by an external clock. The spread spectrum feature is disabled when external synchronization is used.

7.4.4 Down Mode

The TPS61378-Q1 features down mode operation when input voltage is close to or higher than output voltage. In down mode, output voltage is regulated at target value, even when $V_{IN} > V_O$. The TPS61378-Q1 high-side and low-side FETs are switching devices that always work in boost operation, where the isolation FET always works as a linear device.

For boost circuits, on-time or duty cycle is reduced as input voltage approaches output voltage. The TPS61378-Q1 enters down mode when V_{IN} reaches 85% (typical) of V_O voltage at 2.2 MHz. Exiting down mode requires V_{IN} to be reduced below 85% (typical) of V_O voltage at 2.2 MHz.

In normal operation, the isolation FET is fully on.

When down mode is triggered and V_{IN} is less than V_O pin voltage, the OUT pin has a fixed 2 V (typical) above V_O pin voltage. An isolation FET works in LDO mode to regulate V_O pin voltage with a 2-V constant voltage drop.

When down mode is triggered and V_{IN} is 100 mV (typical) higher than V_O pin voltage, the OUT pin has an approximated 3 V (typical) above the V_{IN} pin voltage. As V_{IN} keeps rising, the OUT pin continues rising with 3 V on top of V_{IN} . In addition, an isolation FET works in LDO mode to regulate V_O pin voltage with a voltage differential of the OUT pin and V_O pin.

Refer to [Figure 7-1](#).

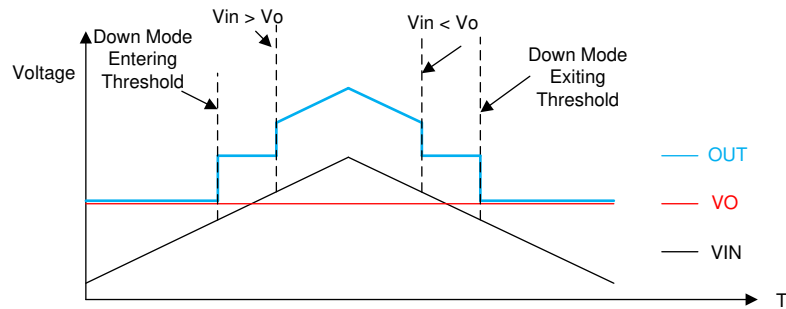


Figure 7-1. Down Mode

Take care during short-to-ground condition when operation V_{IN} is above 6 V. During hiccup on, the device operates in down mode and the isolation FET voltage drop is $V_{IN} + 3\text{ V}$ (OUT pin to VO pin).

8 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.

8.1 Application Information

The TPS61378-Q1 is a 25- μ A quiescent current boost converter that supports a 2.3-V to 14-V input voltage range. The device also supports load disconnect to minimize the leakage current. The following design procedure can be used to select component values for the TPS61378-Q1.

8.2 Typical Application

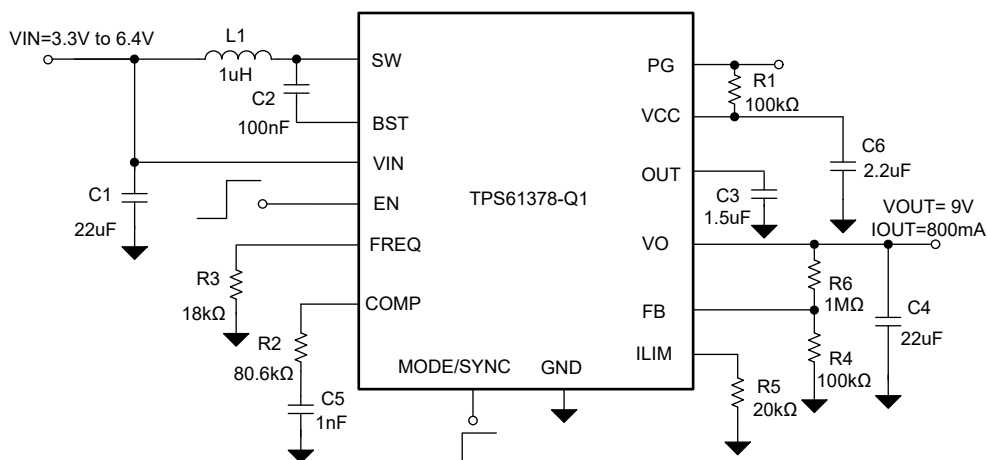


Figure 8-1. Typical Application

8.2.1 Design Requirements

A typical application example is dual cameras powered through a coax cable, which normally requires 9.0-V output as its bias voltage and consumes less than 600 mA current. 800-mA load current is designed to provide margin. The following design procedure can be used to select external component values for the TPS61378-Q1.

Table 8-1. Design Requirements

PARAMETERS	VALUES
Input Voltage	3.3 V to 6.4 V
Output Voltage	9.0 V
Switching Frequency	2.2 MHz
Output Current	800 mA
Output Voltage Ripple	± 25 mV

8.2.2 Detailed Design Procedure

8.2.2.1 Programming the Output Voltage

The output voltage is determined by the resistor sensed from FB pin before device is enabled.

There are two ways to set the output voltage of the TPS61378-Q1, adjustable output voltage(for TPS61378-Q1 and TPS613783-Q1 only) and fixed output voltage.

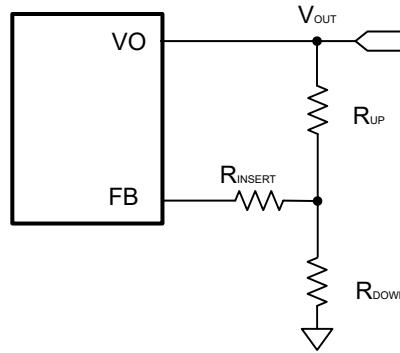


Figure 8-2. Typical Connection of FB Pin For Adjustable Output Voltage

Figure 8-2 shows the typical circuit of the FB pin connection for adjustable output voltage. The FB resistor R_{FB} is defined as Equation 3:

$$R_{FB} = R_{INSERT} + \frac{R_{UP} \times R_{DOWN}}{R_{UP} + R_{DOWN}} \quad (3)$$

When selected for adjustable output voltage, R_{FB} must be above 14.4kΩ. The FB pin is connected to the negative input of the internal error amplifier directly. The output voltage can be programmed by adjusting the external resistor divider R_{UP} and R_{DOWN} according to Equation 4.

$$V_{OUT} = V_{REF} \times \frac{(R_{UP} + R_{DOWN})}{R_{DOWN}} \quad (4)$$

Equation 4 shows that the output voltage setting is only influenced by R_{UP} and R_{DOWN} . In normal application, R_{INSERT} can be 0Ω, that is, directly connect FB pin to middle point of feedback voltage divider.

For automotive application that do not prefer to use resistors more than 100 kΩ, R_{INSERT} (>15kΩ) can be used so that calculated R_{UP} and R_{DOWN} feedback resistor value could be less than 100kΩ.

When working with adjustable voltage, for the best accuracy, R_{DOWN} is recommended to be smaller than 160 kΩ to ensure that the current flowing through R_{DOWN} is at least 100 times larger than FB pin leakage current. Changing R_{DOWN} towards the lower value increases the robustness against noise injection. Changing R_{DOWN} to higher values reduces the quiescent current to achieve higher efficiency at light load.

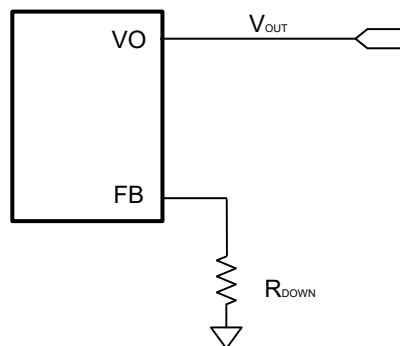


Figure 8-3. Typical Connection of FB Pin For Fixed Output Voltage

Figure 8-3 shows the typical circuit of the FB pin connection for fixed output voltage. The FB resistor R_{FB} is defined as Equation 5:

$$R_{FB} = R_{DOWN} \quad (5)$$

When designed for fixed output voltage, the TPS61378-Q1 uses the internal resistor divider and works with fixed output voltage. The TPS61378-Q1 subdivides the voltage due to R_{FB} and device part number. See [Device Comparison Table](#) for detailed information.

8.2.2.2 Setting the Switching Frequency

The switching frequency of the TPS61378-Q1 is set at 2.2 MHz. Use [Equation 1](#) to calculate the required resistor value. The calculated value is 18 kΩ to get the frequency of 2.2 MHz.

8.2.2.3 Setting the Current Limit

The current limit of the TPS61378-Q1 can be programmed by an external resistor. For a target current limit of 4.8 A, use [Equation 2](#). The calculated resistor value is 20 kΩ.

8.2.2.4 Selecting the Inductor

A boost converter normally requires two main passive components for storing energy during power conversion: an inductor and an output capacitor. The inductor affects the steady state efficiency (including the ripple and efficiency), transient behavior, and loop stability, which makes the inductor the most critical component in application.

When selecting the inductor and the inductance, the other important parameters are:

- The maximum current rating (RMS and peak current should be considered)
- The series resistance
- Operating temperature

The TPS61378-Q1 has built-in slope compensation to avoid subharmonic oscillation associated with current mode control. If the inductor value is too low and makes the inductor peak-to-peak ripple higher than 2 A, the slope compensation may not be adequate, and the loop can be unstable. Therefore, it is recommended to make the peak-to-peak current ripple between 800 mA to 2 A when selecting the inductor.

The inductance can be calculated by [Equation 6](#), [Equation 7](#), and [Equation 8](#):

$$\Delta I_L = \frac{V_{IN} \times D}{L \times f_{SW}} \quad (6)$$

$$\Delta I_{L_R} = \text{Ripple\%} \times \frac{V_{OUT} \times I_{OUT}}{\eta \times V_{IN}} \quad (7)$$

$$L = \frac{1}{\text{Ripple \%}} \times \frac{\eta \times V_{IN}}{V_{OUT} \times I_{OUT}} \times \frac{V_{IN} \times D}{f_{SW}} \quad (8)$$

where

- ΔI_L is the peak-peak inductor current ripple
- V_{IN} is the input voltage
- D is the duty cycle
- L is the inductor
- f_{SW} is the switching frequency
- Ripple % is the ripple ration versus the DC current
- V_{OUT} is the output voltage
- I_{OUT} is the output current
- η is the efficiency

The current flowing through the inductor is the inductor ripple current plus the average input current. During power up, load faults, or transient load conditions, the inductor current can increase above the peak inductor current calculated.

Inductor values can have $\pm 20\%$, or even $\pm 30\%$, tolerance with no current bias. When the inductor current approaches the saturation level, the inductance can decrease 20% to 35% from the value at 0-A bias current, depending on how the inductor vendor defines saturation. When selecting an inductor, make sure the rated current, especially the saturation current, is larger than its peak current during the operation.

The inductor peak current varies as a function of the load, switching frequency, and input and output voltages. The peak current can be calculated with [Equation 9](#) and [Equation 10](#).

$$I_{PEAK} = I_{IN} + \frac{1}{2} \times \Delta I_L \quad (9)$$

where

- I_{PEAK} is the peak current of the inductor
- I_{IN} is the input average current
- ΔI_L is the ripple current of the inductor

The input DC current is determined by the output voltage. The output current can be calculated by:

$$I_{IN} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times \eta} \quad (10)$$

where

- I_{IN} is the input current of the inductor
- V_{OUT} is the output voltage
- V_{IN} is the input voltage
- η is the efficiency

While the inductor ripple current depends on the inductance, the frequency, the input voltage, and duty cycle are calculated by [Equation 6](#). Replace [Equation 6](#) and [Equation 10](#) into [Equation 9](#) and get the inductor peak current:

$$I_{PEAK} = \frac{I_{OUT}}{(1-D) \times \eta} + \frac{1}{2} \times \frac{V_{IN} \times D}{L \times f_{SW}} \quad (11)$$

where

- I_{PEAK} is the peak current of the inductor
- I_{OUT} is the output current
- D is the duty cycle
- η is the efficiency
- V_{IN} is the input voltage
- L is the inductor
- f_{SW} is the switching frequency

The heat rating current (RMS) is can be calculated with [Equation 12](#):

$$I_{L_RMS} = \sqrt{I_{IN}^2 + \frac{1}{12} (\Delta I_L)^2} \quad (12)$$

where

- I_{L_RMS} is the RMS current of the inductor
- I_{IN} is the input current of the inductor
- ΔI_L is the ripple current of the inductor

It is important that the peak current does not exceed the inductor saturation current and the RMS current is not over the temperature-related rating current of the inductors.

For a given physical inductor size, increasing inductance usually results in an inductor with lower saturation current. The total losses of the coil consists of the DC resistance (DCR) loss and the following frequency-dependent loss:

- The losses in the core material (magnetic hysteresis loss, especially at high switching frequencies)
- Additional losses in the conductor from the skin effect (current displacement at high frequencies)
- Magnetic field losses of the neighboring windings (proximity effect)

For a certain inductor, the larger current ripple (smaller inductor) generates the higher DC and also the frequency-dependent loss. An inductor with lower DCR is basically recommended for higher efficiency. However, it is usually a tradeoff between the loss and foot print. [Table 8-2](#) lists some recommended inductors.

Table 8-2. Recommended Inductors

PART NUMBER	L (μH)	DCR TYP (mΩ) MAX	SATURATION CURRENT (A)	SIZE (L × W × H mm)	VENDOR ⁽¹⁾
XEL4030-471MEB	0.47	4.1	15.5	4 × 4 × 3	Coilcraft
XEL4030-102MEB	1	8.9	9	4 × 4 × 3	Coilcraft
DFE2HCAHR47MJ0L	0.47	25	5.1	2.5 × 2 × 1.2	Murata
DFE322520FD-1R0M	1	22	7.5	3.2 × 2.5 × 2	Murata
TFM322512ALMAR47MTAA	0.47	16	7.6	3.2 × 2.5 × 1.2	TDK
TFM322512ALMA1R0MTAA	1	30	5.1	3.2 × 2.5 × 1.2	TDK

(1) See the [Third-party Products Disclaimer](#).

8.2.2.5 Selecting the Output Capacitors

The output capacitor is mainly selected to meet the requirements at load transient or steady state. The loop is compensated for the output capacitor selected. The output ripple voltage is related to the equivalent series resistance (ESR) of the capacitor and its capacitance. Assuming a capacitor with zero ESR, the minimum capacitance needed for a given ripple can be calculated by [Equation 13](#):

$$C_{OUT} = \frac{I_{OUT} \times (V_{OUT} - V_{IN})}{f_{SW} \times \Delta V \times V_{OUT}} \quad (13)$$

where

- C_{OUT} is the output capacitor
- I_{OUT} is the output current
- V_{OUT} is the output voltage
- V_{IN} is the input voltage
- ΔV is the output voltage ripple required
- f_{SW} is the switching frequency

The additional output ripple component caused by ESR is calculated by [Equation 14](#):

$$\Delta V_{ESR} = I_{OUT} \times R_{ESR} \quad (14)$$

where

- ΔV_{ESR} is the output voltage ripple caused by ESR
- R_{ESR} is the resistor in series with the output capacitor

For the ceramic capacitor, the ESR ripple can be neglected. However, for the tantalum or electrolytic capacitors, it must be considered if used.

The minimum ceramic output capacitance needed to meet a load transient requirement can be estimated using [Equation 15](#):

$$C_{OUT} = \frac{\Delta I_{STEP}}{2\pi \times f_{BW} \times \Delta V_{TRAN}} \quad (15)$$

where

- ΔI_{STEP} is the transient load current step
- ΔV_{TRAN} is the allowed voltage dip for the load current step
- f_{BW} is the control loop bandwidth (that is, the frequency where the control loop gain crosses zero)

For the output capacitor on the OUT pin, the effective capacitance is recommended between 0.22 μF to 1 μF .

Take care when evaluating the derating of a ceramic capacitor under the DC bias. Ceramic capacitors can derate by as much as 70% of the capacitance at the respective rated voltage. Therefore, enough margins on the voltage rating must be considered to ensure adequate capacitance at the required output voltage.

8.2.2.6 Selecting the Input Capacitors

Multilayer ceramic capacitors are an excellent choice for the input decoupling of the step-up converter since they have extremely low ESR and are available in small footprints. Input capacitors must be located as close as possible to the device. While a 22- μF input capacitor or equivalent is sufficient for the most applications, larger values can be used to reduce input current ripple.

Take care when using only ceramic input capacitors. When a ceramic capacitor is used at the input and the power is being supplied through long wires, such as from a wall adapter, a load step at the output can induce ringing at the VIN pin. This ringing can couple to the output and be mistaken as loop instability or can even damage the device. Additional "bulk" capacitance (electrolytic or tantalum) in this circumstance, must be placed between C_{IN} and the power source lead to reduce ringing that can occur between the inductance of the power source leads and C_{IN} .

8.2.2.7 Loop Stability and Compensation

8.2.2.7.1 Small Signal Model

The TPS61378-Q1 uses the fixed frequency peak current mode control. There is an internal adaptive slope compensation to avoid subharmonic oscillation. With the inductor current information sensed, the small-signal model of the power stage reduces from a two-pole system, created by L and C_{OUT} , to a single-pole system, created by R_{OUT} and C_{OUT} . The single-pole system is easily used with the loop compensation. Figure 8-4 shows the equivalent small signal elements of a boost converter.

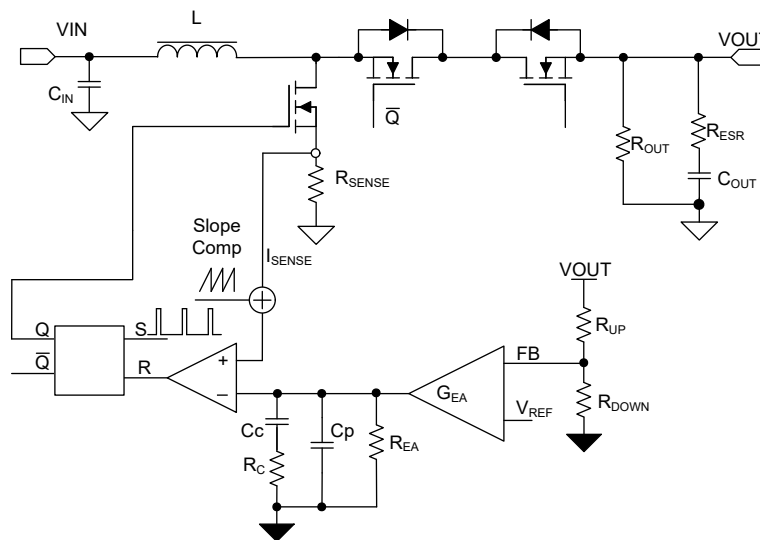


Figure 8-4. TPS61378-Q1 Control Equivalent Circuitry Model

The small signal of power stage is:

$$K_{PS}(S) = \frac{R_{OUT} \times (1 - D)}{2 \times R_{SENSE}} \times \frac{(1 + \frac{S}{2\pi \times f_{ESR}})(1 - \frac{S}{2\pi \times f_{RHP}})}{(1 + \frac{S}{2\pi \times f_p})} \quad (16)$$

where

- D is the duty cycle
- R_{OUT} is the output load resistor
- R_{SENSE} is the equivalent internal current sense resistor, which is typically 118 mΩ

The single pole of the power stage is:

$$f_P = \frac{2}{2\pi \times R_{OUT} \times C_{OUT}} \quad (17)$$

where

- C_{OUT} is the output capacitance. For a boost converter having multiple identical output capacitors in parallel, simply combine the capacitors with the equivalent capacitance

The zero created by the ESR of the output capacitor is:

$$f_{ESR} = \frac{1}{2\pi \times R_{ESR} \times C_{OUT}} \quad (18)$$

where

- R_{ESR} is the equivalent resistance in series of the output capacitor

The right-hand plane zero is:

$$f_{RHP} = \frac{R_{OUT} \times (1 - D)^2}{2\pi \times L} \quad (19)$$

where

- D is the duty cycle
- R_{OUT} is the output load resistor
- L is the inductance

Equation 20 shows the equation for feedback resistor network and the error amplifier.

$$H_{EA}(S) = G_{EA} \times R_{EA} \times \frac{R_{DOWN}}{R_{UP} + R_{DOWN}} \times \frac{1 + \frac{S}{2 \times \pi \times f_Z}}{\left(1 + \frac{S}{2 \times \pi \times f_{P1}}\right) \times \left(1 + \frac{S}{2 \times \pi \times f_{P2}}\right)} \quad (20)$$

where

- R_{EA} is the output impedance of the error amplifier, typically $R_{EA} = 500 \text{ M}\Omega$
- f_{P1} , f_{P2} is the pole's frequency of the compensation
- f_Z is the zero's frequency of the compensation network

$$f_{P1} = \frac{1}{2\pi \times R_{EA} \times C_C} \quad (21)$$

where

- C_C is the zero capacitor compensation

$$f_{P2} = \frac{1}{2\pi \times R_C \times C_P} \quad (22)$$

where

- C_P is the pole capacitor compensation
- R_C is the resistor of the compensation network

$$f_Z = \frac{1}{2\pi \times R_C \times C_C} \quad (23)$$

8.2.2.7.2 Loop Compensation Design Steps

With the small signal models coming out, the next step is to calculate the compensation network parameters with the given inductor and output capacitance.

1. Set the Crossover Frequency, f_C .

The first step is to set the loop crossover frequency, f_C . The higher the crossover frequency, the faster the loop response is. It is generally accepted that the loop gain crosses over no higher than the lower of either 1/10 of the switching frequency, f_{SW} , or 1/5 of the RHPZ frequency, f_{RHPZ} . Then, calculate the loop compensation network values of R_C , C_C , and C_P by the following equations.

2. Set the Compensation Resistor, R_C .

By placing f_Z below f_C , for frequencies above f_C , $R_C \parallel R_{EA} \approx R_C$, so $R_C \times G_{EA}$ sets the compensation gain. Setting the compensation gain, $K_{COMP-dB}$, at f_Z results in the total loop gain, $T(s) = K_{PS}(s) \times H_{EA}(s)$, being zero at f_C .

Therefore, to approximate a single-pole rolloff up to f_{P2} , rearrange Equation 20 to solve for R_C so that the compensation gain, K_{EA} , at f_C is the negative of the gain, K_{PS} . Read at frequency f_C for the power stage bode plot or more simply:

$$K_{EA}(f_C) = 20 \times \log(G_{EA} \times R_C \times \frac{R_{DOWN}}{R_{UP} + R_{DOWN}}) = -K_{PS}(f_C) \quad (24)$$

where

- K_{EA} is gain of the error amplifier network
 - K_{PS} is the gain of the power stage
 - G_{EA} is the transconductance of the amplifier, the typical value of $G_{EA} = 70 \mu A / V$
- ##### 3. Set the Compensation Zero capacitor, C_C .

Place the compensation zero at the power stage R_{OUT} , C_{OUT} pole's position to get:

$$f_Z = \frac{1}{2\pi \times R_C \times C_C} \quad (25)$$

$$C_C = \frac{R_{OUT} \times C_{OUT}}{2R_C} \quad (26)$$

4. Set the Compensation Pole Capacitor, C_P .

Place the compensation pole at the zero produced by R_{ESR} and C_{OUT} . It is useful for canceling unhelpful effects of the ESR zero.

$$f_{P2} = \frac{1}{2\pi \times R_C \times C_P} \quad (27)$$

$$f_{\text{ESR}} = \frac{1}{2\pi \times R_{\text{ESR}} \times C_{\text{OUT}}} \quad (28)$$

Set $f_{\text{P2}} = f_{\text{ESR}}$, and get:

$$C_{\text{P}} = \frac{R_{\text{ESR}} \times C_{\text{OUT}}}{R_{\text{C}}} \quad (29)$$

8.2.2.7.3 Selecting the Bootstrap Capacitor

The bootstrap capacitor between the BST and SW pin supplies the gate current to charge the high-side FET device gate during the turnon of each cycle. The gate current also supplies charge for the bootstrap capacitor. The recommended value of the bootstrap capacitor is 0.1 μF to 1 μF . C_{BST} must be a good quality, low-ESR ceramic capacitor located at the pins of the device to minimize potentially damaging voltage transients caused by trace inductance. A value of 0.1 μF was selected for this design example.

8.2.2.7.4 V_{CC} Capacitor

The primary purpose of the V_{CC} capacitor is to supply the peak transient currents of the driver and bootstrap capacitor and provide stability for the V_{CC} regulator. The value of C_{VCC} must be at least 10 times greater than the value of C_{BST} , and must be a good quality, low-ESR ceramic capacitor. C_{VCC} must be placed close to the pins of the IC to minimize potentially damaging voltage transients caused by the trace inductance. A value of 2.2 μF was selected for this design example.

8.2.3 Application Curves

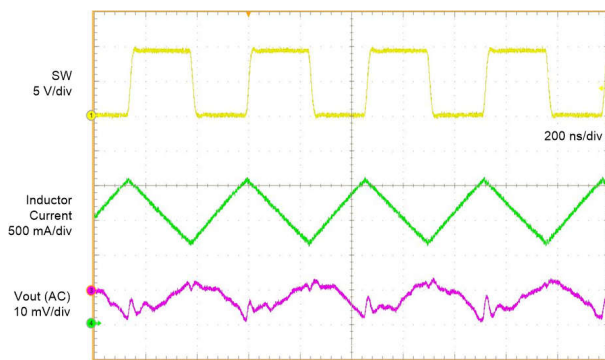


Figure 8-5. Switching Waveform $V_{\text{IN}} = 5 \text{ V}$, $V_{\text{OUT}} = 9 \text{ V}$, $I_{\text{OUT}} = 800 \text{ mA}$, FPWM

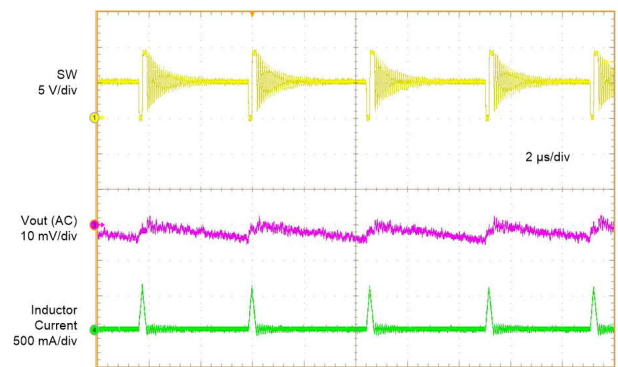


Figure 8-6. Switching Waveform $V_{\text{IN}} = 5 \text{ V}$, $V_{\text{OUT}} = 9 \text{ V}$, $I_{\text{OUT}} = 0 \text{ mA}$, Auto PFM

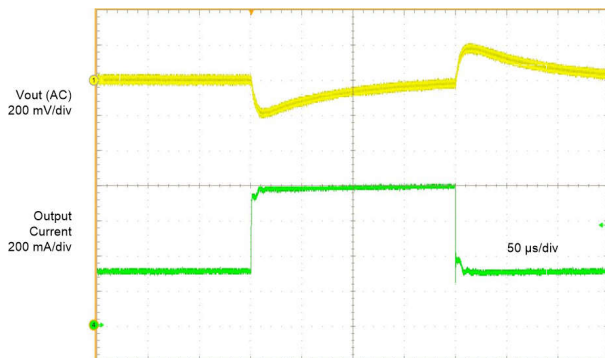


Figure 8-7. Load Transient $V_{\text{IN}} = 5 \text{ V}$, $V_{\text{OUT}} = 9 \text{ V}$, $I_{\text{OUT}} = 300 \text{ mA}$ to 800 mA , FPWM

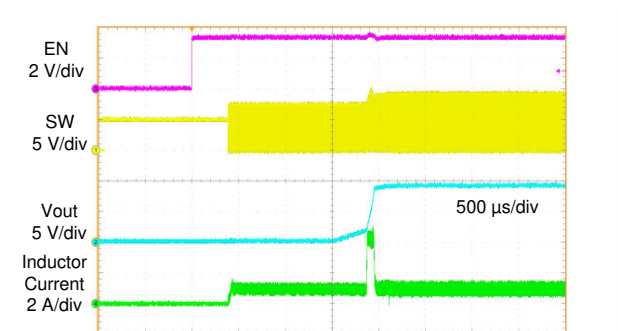


Figure 8-8. Start-up from EN Waveform $V_{\text{IN}} = 5 \text{ V}$, $V_{\text{OUT}} = 9 \text{ V}$, $I_{\text{OUT}} = 500 \text{ mA}$, FPWM

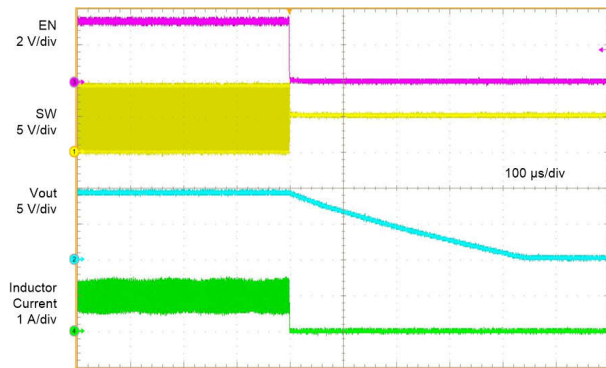


Figure 8-9. Shutdown from EN Waveforms
 $V_{IN} = 5\text{ V}$, $V_{OUT} = 9\text{ V}$, $I_{OUT} = 500\text{ mA}$, FPWM

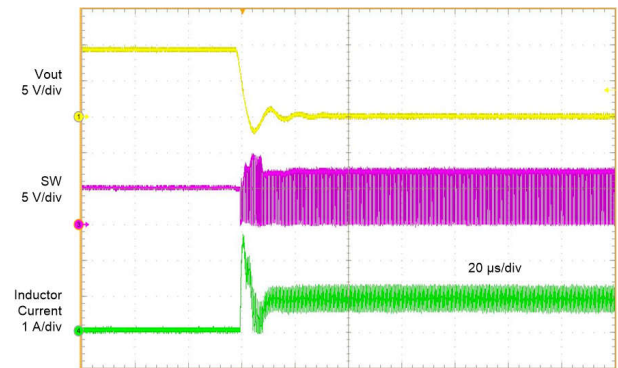


Figure 8-10. Short Circuit Protection $V_{IN} = 5\text{ V}$, $V_{OUT} = 9\text{ V}$, FPWM

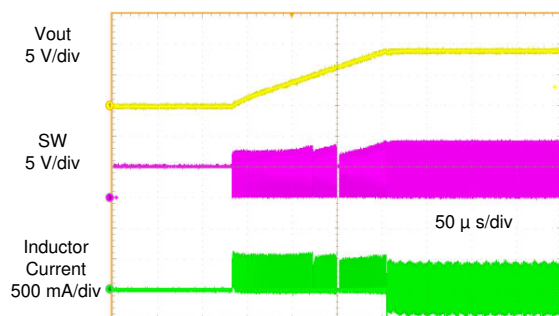


Figure 8-11. Short Circuit Recovery $V_{IN} = 5\text{ V}$, $V_{OUT} = 9\text{ V}$, $I_{OUT} = 0\text{ mA}$, FPWM

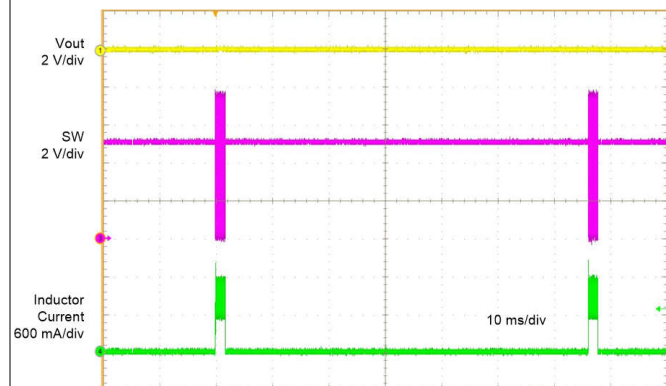


Figure 8-12. Hiccup Short Circuit Protection
 $V_{IN} = 5\text{ V}$, $V_{OUT} = 9\text{ V}$, FPWM

9 Power Supply Recommendations

The TPS61378-Q1 is designed to operate from an input voltage supply range between 2.3 V to 14 V. This input supply must be well regulated. If the input supply is located more than a few inches from the device, the bulk capacitance can be required in addition to the ceramic bypass capacitors. An electrolytic capacitor with a value of 47 μF is a typical choice.

10 Layout

10.1 Layout Guidelines

As for all switching power supplies, the layout is an important step in the design, especially at high peak currents and high switching frequencies. If the layout is not carefully done, the regulator can show stability problems as well as EMI problems. Therefore, use wide and short traces for the main current path and for the power ground paths. The input and output capacitor, as well as the inductor must be placed as close as possible to the IC.

10.2 Layout Example

The bottom layer is a large GND plane connected by vias.

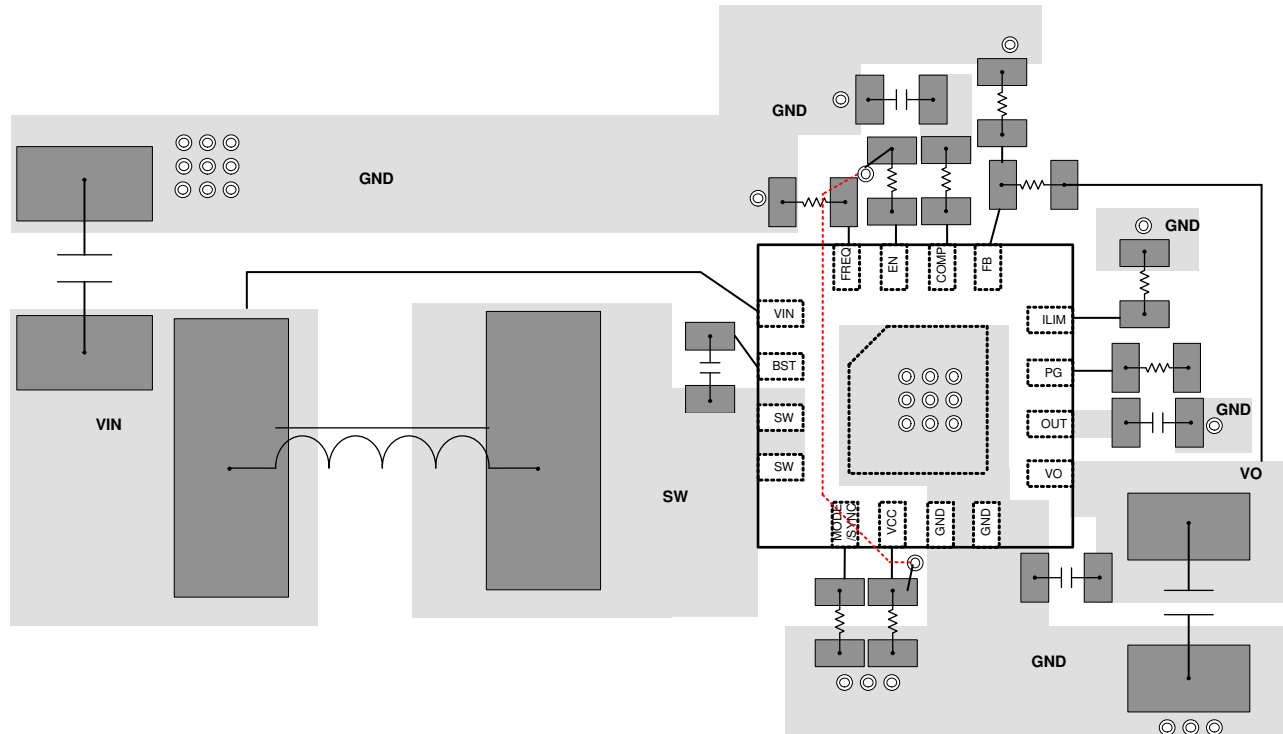


Figure 10-1. Recommended Layout

11 Device and Documentation Support

11.1 Device Support

11.1.1 Third-Party Products Disclaimer

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11.2 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.

11.3 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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11.5 Glossary

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

11.6 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.

12 Revision History

Changes from Revision D (October 2021) to Revision E (October 2024)	Page
• Added TPS61378L.....	1
• Added additional features.....	1
• Updated Package to WQFN-16.....	1
• Updated Output Voltage Selection Resistor in the Device Comparison Table.....	3
• Updated Error Amplifier units.....	6
• Updated Figure 6-8	8
• Added additional information to Spread Spectrum Frequency Modulation.....	13
• Added Table 7-1	13
• Added additional information to Output Short Protection/Hiccup.....	14
• Added "The external clock needs to be within +20% of the setting frequency to ensure a reliable synchronization.".....	15
• Updated Figure 8-1	17
• Added additional information and Figure 8-2 and Figure 8-3	17

Changes from Revision C (June 2021) to Revision D (October 2021)	Page
• Updated Section 7.3.13	14
• Updated Figure 8-4	22

Changes from Revision B (February 2021) to Revision C (June 2021)	Page
• Updated resistor from FB to GND values.....	3
• Updated Section 8.2.2.1	17

13 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 devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

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)
TPS613783QWRTERQ1	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2G8H
TPS613783QWRTERQ1.A	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2G8H
TPS613785QWRTERQ1	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2G9H
TPS613785QWRTERQ1.A	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2G9H
TPS61378LQWRTERQ1	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	SN	Level-1-260C-UNLIM	-40 to 125	61378L
TPS61378LQWRTERQ1.A	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	SN	Level-1-260C-UNLIM	-40 to 125	61378L
TPS61378QWRTERQ1	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2ELH
TPS61378QWRTERQ1.A	Active	Production	WQFN (RTE) 16	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	2ELH

⁽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.

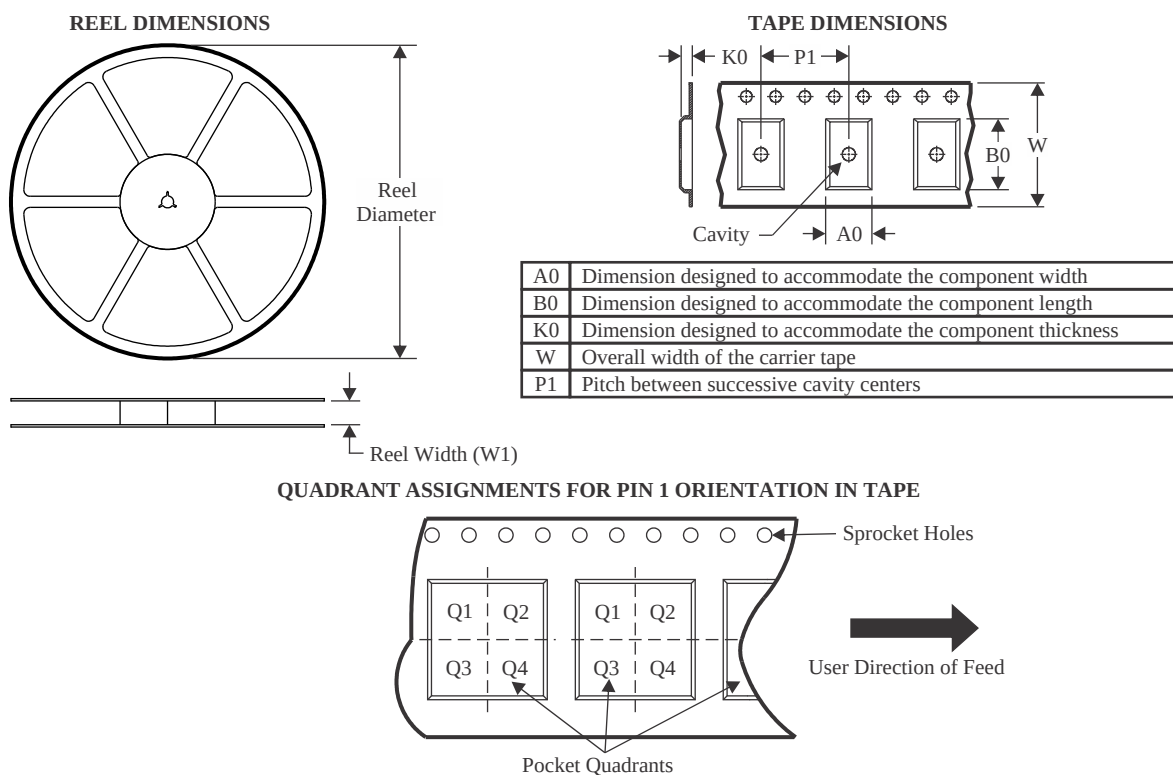
⁽⁶⁾ **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

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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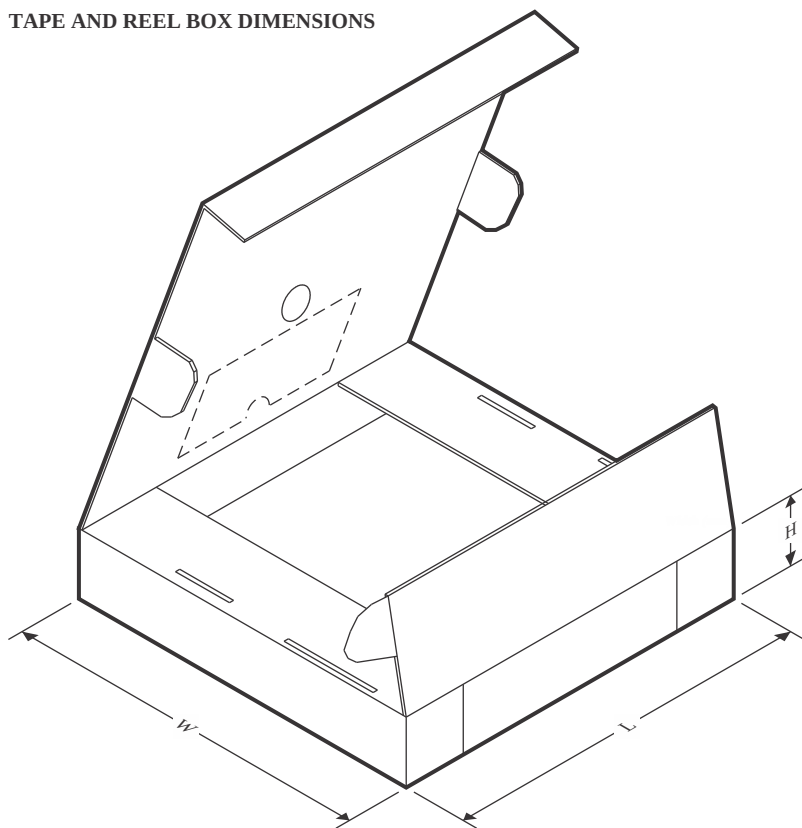
TAPE AND REEL INFORMATION



*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
TPS613783QWRTERQ1	WQFN	RTE	16	3000	330.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2
TPS613785QWRTERQ1	WQFN	RTE	16	3000	330.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2
TPS61378LQWRTERQ1	WQFN	RTE	16	3000	330.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2
TPS61378QWRTERQ1	WQFN	RTE	16	3000	330.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2

TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
TPS613783QWRTERQ1	WQFN	RTE	16	3000	367.0	367.0	35.0
TPS613785QWRTERQ1	WQFN	RTE	16	3000	367.0	367.0	35.0
TPS61378LQWRTERQ1	WQFN	RTE	16	3000	367.0	367.0	35.0
TPS61378QWRTERQ1	WQFN	RTE	16	3000	367.0	367.0	35.0

GENERIC PACKAGE VIEW

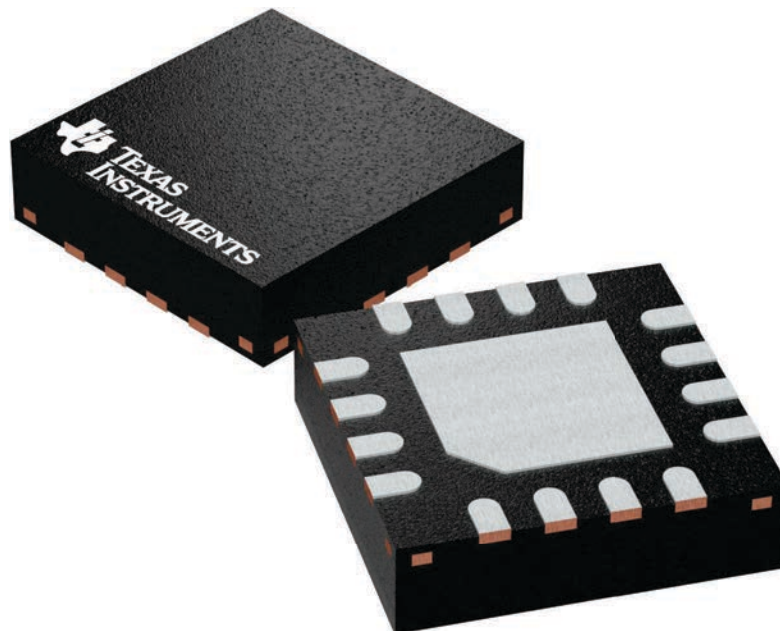
RTE 16

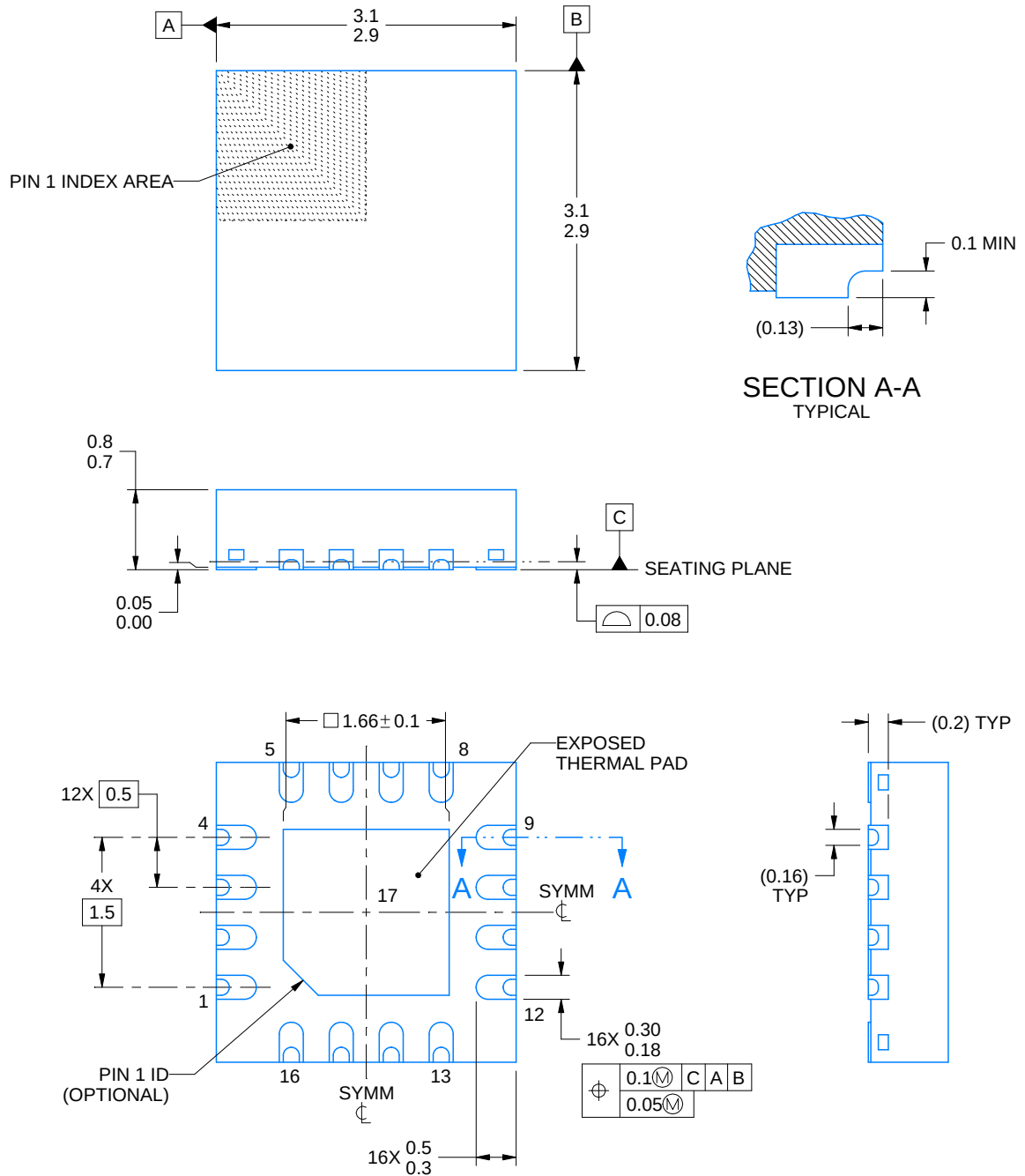
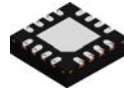
WQFN - 0.8 mm max height

3 x 3, 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.





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NOTES:

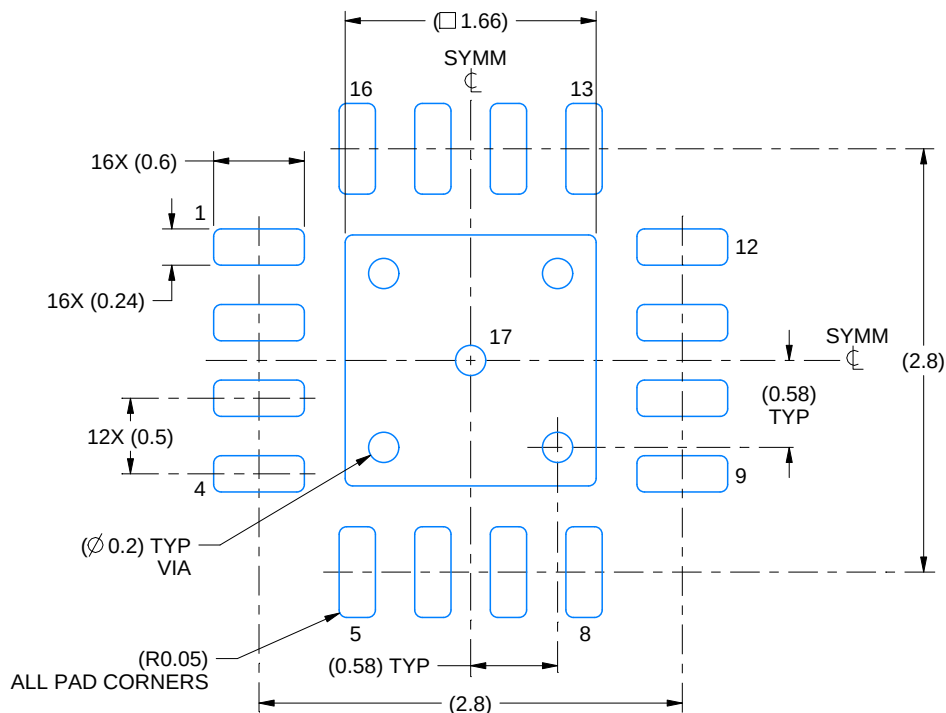
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. The package thermal pad must be soldered to the printed circuit board for thermal and mechanical performance.

EXAMPLE BOARD LAYOUT

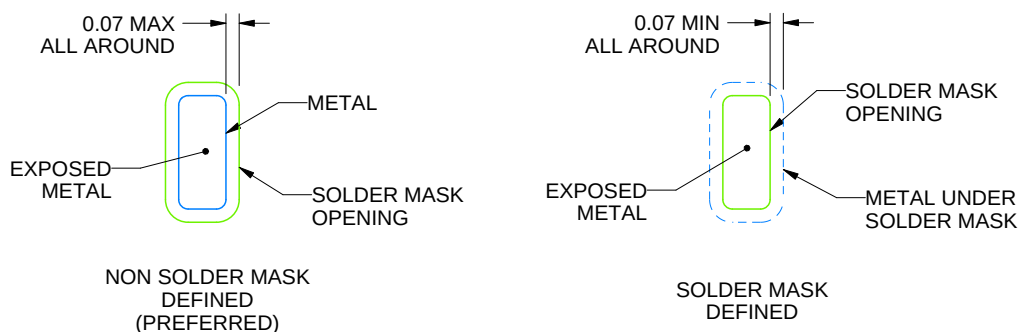
RTE0016K

WQFN - 0.8 mm max height

PLASTIC QUAD FLATPACK - NO LEAD



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:20X



SOLDER MASK DETAILS

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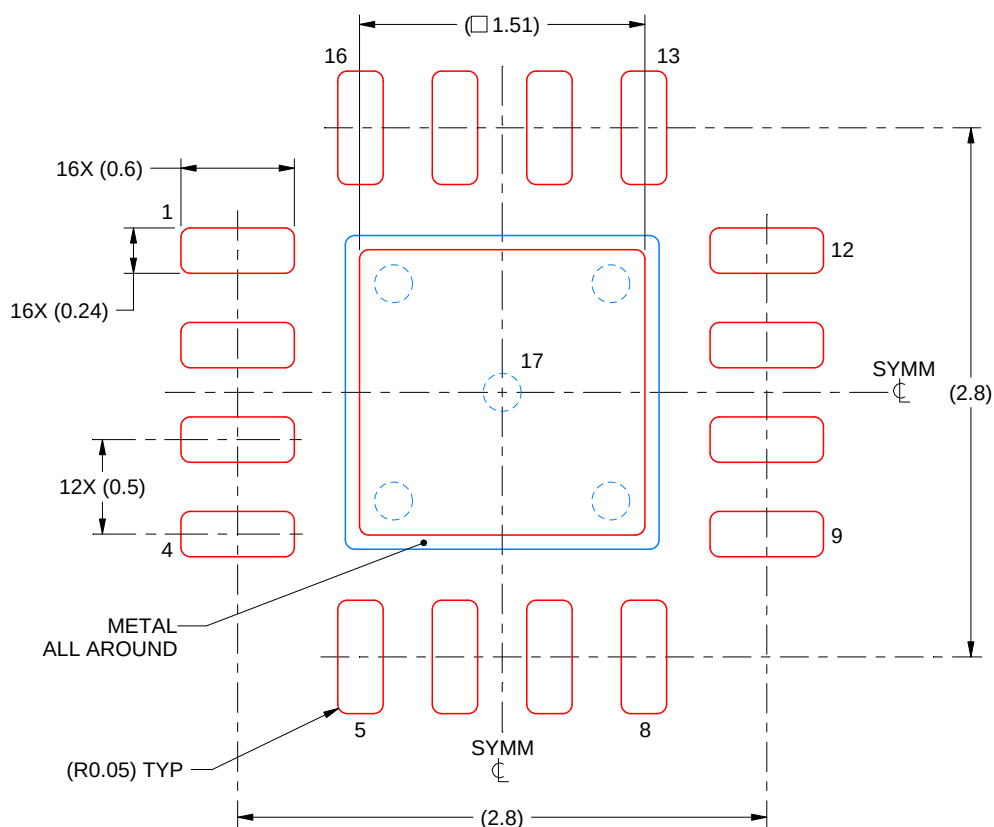
NOTES: (continued)

- This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature number SLUA271 (www.ti.com/lit/sluea271).
- Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It is recommended that vias under paste be filled, plugged or tented.

RTE0016K

WQFN - 0.8 mm max height

PLASTIC QUAD FLATPACK - NO LEAD



SOLDER PASTE EXAMPLE BASED ON 0.125 mm THICK STENCIL

EXPOSED PAD 17:
84% PRINTED SOLDER COVERAGE BY AREA UNDER PACKAGE
SCALE:25X

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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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