2A Dual Channel Synchronous Step-Down Switcher with Integrated FET

Check for Samples: TPS54294

FEATURES

- **D-CAP2™ Control Mode**
  - **Fast Transient Response**
  - **No External Parts Required For Loop Compensation**
  - **Compatible with Ceramic Output Capacitors**
- **Wide Input Voltage Range : 4.5 V to 18 V**
- **Output Voltage Range : 0.76V to 7.0V**
- **Highly Efficient Integrated FETs Optimized for Low Duty Cycle Applications**
  - **150 mΩ (High Side) and 100 mΩ (Low Side)**
- **High Initial Reference Accuracy**
- **Low-Side $r_{DS(on)}$ Loss-Less Current Sensing**
- **Fixed Soft Start : 1.0ms**
- **Non-Sinking Pre-Biased Soft Start**
- **Powergood**
- **700 kHz Switching Frequency**
- **Cycle-by-Cycle Over-Current Limit Control**
- **OCL/OVP/UVP/UVLO/TSD Protections**
- **Adaptive Gate Drivers with Integrated Boost PMOS Switch**
- **OCP Constant Due To Thermally Compensated $r_{DS(on)}$ with 4000ppm/℃**
- **16-Pin HTSSOP, 16-Pin VQFN**
- **Auto-Skip Eco-mode™ for High Efficiency at Light Load**

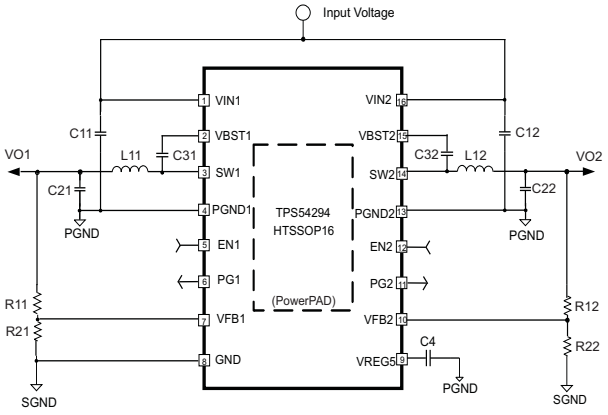
APPLICATIONS

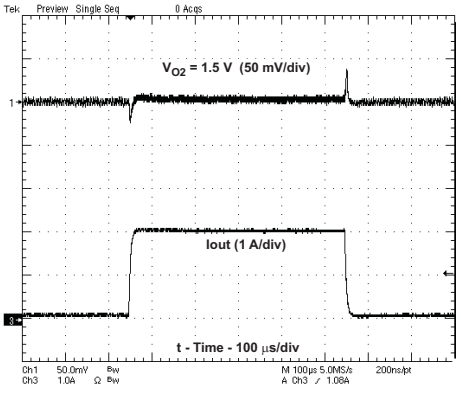
- **Point-of-Load Regulation in Low Power Systems for Wide Range of Applications**
  - **Digital TV Power Supply**
  - **Networking Home Terminal**
  - **Digital Set Top Box (STB)**
  - **DVD Player/Recorder**
  - **Gaming Consoles and Other**

DESCRIPTION

The TPS54294 is a dual, adaptive on-time D-CAP2™ mode synchronous buck converter. The TPS54294 enables system designers to complete the suite of various end equipment's power bus regulators with a cost effective, low component count, and low standby current solution. The main control loops of the TPS54294 use the D-CAP2™ mode control which provides a very fast transient response with no external compensation components. The adaptive on-time control supports seamless transition between PWM mode at higher load conditions and Eco-mode™ operation at light loads. Eco-mode™ allows the TPS54294 to maintain high efficiency during lighter load conditions. The TPS54294 is able to adapt to both low equivalent series resistance (ESR) output capacitors such as POSCAP or SP-CAP, and ultra-low ESR, ceramic capacitors. The device provides convenient and efficient operation with input voltages from 4.5V to 18V.

The TPS54294 is available in a 4.4mm × 5.0mm 16-pin TSSOP (PWP) package, and 4mm x 4mm 16-pin VQFN (RSA) package specified for an ambient temperature range from –40°C to 85°C.





Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

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These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

ORDERING INFORMATION(1)

T_A	PACKAGE	ORDERING PART NUMBER	PINS	OUTPUT SUPPLY
–40°C to 85°C	PWP	TPS54294PWPR	16	Tape-and-Reel
		TPS54294PWP		Tube
	RSA	TPS54294RSAR	16	Tape-and-Reel
		TPS54294RSAT		

(1) For the most current package and ordering information, see the Package Option Addendum at the end of this document, or see the TI web site at www.ti.com

ABSOLUTE MAXIMUM RATINGS

over operating free-air temperature range (unless otherwise noted)(1) (2)

		VALUE	UNIT
Input voltage range	VIN1, VIN2, EN1, EN2	–0.3 to 20	V
	VBST1, VBST2	–0.3 to 26	
	VBST1, VBST2 (10ns transient)	–0.3 to 28	
	VBST1–SW1 , VBST2–SW2	–0.3 to 6.5	
	VFB1, VFB2	–0.3 to 6.5	
	SW1, SW2	–2 to 20	
	SW1, SW2 (10ns transient)	–3 to 22	
Output voltage range	VREG5, PG1, PG2	–0.3 to 6.5	V
	PGND1, PGND2	–0.3 to 0.3	
Electrostatic discharge	Human Body Model (HBM)	2	kV
	Charged Device Model (CDM)	500	V
T_A	Operating ambient temperature range	–40 to 85	°C
T_{STG}	Storage temperature range	–55 to 150	°C
T_J	Junction temperature range	–40 to 150	°C

(1) Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" are not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) All voltages are with respect to IC GND terminal.

THERMAL INFORMATION

THERMAL METRIC(1)		TPS54294		UNITS
		PWP (16) PINS	RSA (16) PINS	
θ_{JA}	Junction-to-ambient thermal resistance	47.5	34.9	°C/W
θ_{JCtop}	Junction-to-case (top) thermal resistance	27.1	40.0	
θ_{JB}	Junction-to-board thermal resistance	20.8	11.8	
ψ_{JT}	Junction-to-top characterization parameter	1.0	0.7	
ψ_{JB}	Junction-to-board characterization parameter	20.6	11.8	
θ_{JCbot}	Junction-to-case (bottom) thermal resistance	2.7	3.3	

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.

RECOMMENDED OPERATING CONDITIONS

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

			VALUES		UNIT
			MIN	MAX	
	Supply input voltage range	VIN1, VIN2	4.5	18	V
	Input voltage range	VBST1, VBST2	–0.1	24	V
		VBST1, VBST2 (10ns transient)	–0.1	27	
		VBST1–SW1, VBST2–SW2	–0.1	5.7	
		VFB1, VFB2	–0.1	5.7	
		EN1, EN2	–0.1	18	
		SW1, SW2	–1.0	18	
		SW1, SW2 (10ns transient)	–3	21	
	Output voltage range	VREG5, PG1 , PG2	–0.1	5.7	V
		PGND1, PGND2	–0.1	0.1	
		VO1, VO2	0.76	7.0	
T_A	Operating free-air temperature		–40	85	°C
T_J	Operating Junction Temperature		–40	150	°C

ELECTRICAL CHARACTERISTICS(1)

over recommended free-air temperature range, VIN = 12 V (unless otherwise noted)

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
SUPPLY CURRENT						
I_{IN}	VIN supply current	EN1 = EN2 = 5 V, VFB1 = VFB2 = 0.8 V		1300	2500	µA
I_{VINSDN}	VIN shutdown current	EN1 = EN2 = 0 V		80	200	µA
FEEDBACK VOLTAGE						
$V_{VFBTHLx}$	VFBx threshold voltage	CH1 = 3.3 V, CH2 = 1.5 V	758	765	773	mV
TC_{VFBx}	Temperature coefficient	On the basis of 25°C(2)	–115		115	ppm/°C
I_{VFBx}	VFB Input Current	VFBx = 0.8 V	–0.35	0.2	0.35	µA
VREG5 OUTPUT						
V_{VREG5}	VREG5 output voltage	6 V < VIN1 < 18 V, I_{VREG} = 5 mA		5.5		V
I_{VREG5}	Output current	VIN1 = 6 V, VREG5 = 4 V(2)		75		mA
MOSFETs						
$r_{DS(on)H}$	High side switch resistance	VBSTx-SWx = 5.5 V (2)		150		mΩ
$r_{DS(on)L}$	Low side switch resistance (2)			100		mΩ
ON-TIME TIMER CONTROL						
T_{ON1}	SW1 On Time	SW1 = 12 V, VO1 = 1.2 V		165		ns
T_{ON2}	SW2 On Time	SW2 = 12 V, VO2 = 1.2 V		165		ns
T_{OFF1}	SW1 Min off time	VFB1 = 0.7 V(2)		220		ns
T_{OFF2}	SW2 Min off time	VFB2 = 0.7 V(2)		220		ns
SOFT START						
T_{SS}	Soft-start time	Internal soft-start time		1.0		ms

(1) x means either 1 or 2, that is, VFBx means VFB1 or VFB2.
(2) Specified by design. Not production tested.

ELECTRICAL CHARACTERISTICS (continued)

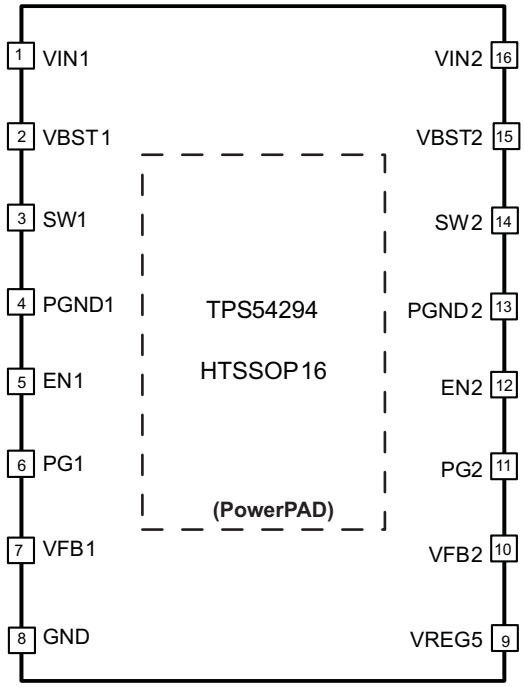
over recommended free-air temperature range, VIN = 12 V (unless otherwise noted)

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
POWER GOOD						
V_{PGTH}	PGx threshold	PG from lower VOx (going high)		84%		
		PG from higher VOx (going low)		116%		
R_{PG}	PGx pull-down resistance	VPGx = 0.5 V	50	75	110	Ω
T_{PGDLY}	PGx delay time	Delay for PGx going high		1.5		ms
		Delay for PGx going low		2		µs
$T_{PGCOMPSS}$	PGx comparator start-up delay	PGx comparator wake-up delay		1.5		ms
UVLO						
V_{UVREG5}	VREG5 UVLO threshold	VREG5 rising		3.83		V
		Hysteresis		0.6		
LOGIC THRESHOLDs						
V_{ENH}	ENx H-level threshold voltage		2.0			V
V_{ENL}	ENx L-level threshold voltage				0.4	V
R_{ENx_IN}	ENx input resistance	ENx = 12 V	225	450	900	kΩ
CURRENT LIMITs						
I_{OCL}	Current limit	L_{OUT} = 2.2 µH(3)	2.7	3.9	4.5	A
OUTPUT UNDERVOLTAGE AND OVERVOLTAGE PROTECTION (UVP, OVP)						
V_{OVP}	Output OVP trip threshold	measured on VFBx	115%	120%	125%	
T_{OVPDEL}	Output OVP prop delay			3	10	µs
V_{UVP}	Output UVP trip threshold	measured on VFBx	63%	68%	73%	
T_{UVPDEL}	Output UVP delay time			1.5		ms
T_{UVPEN}	Output UVP enable delay			1.5		ms
THERMAL SHUTDOWN						
T_{SD}	Thermal shutdown threshold	Shutdown temperature(3)		155		°C
		Hysteresis(3)		25		

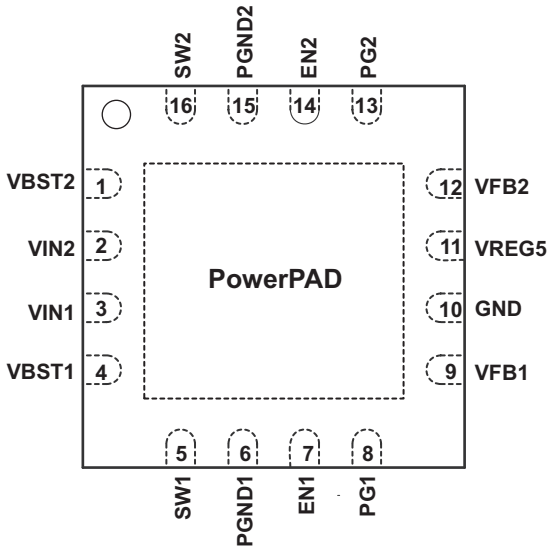
(3) Specified by design. Not production tested.

DEVICE INFORMATION

HTSSOP PACKAGE (TOP VIEW)



RSA PACKAGE (TOP VIEW)

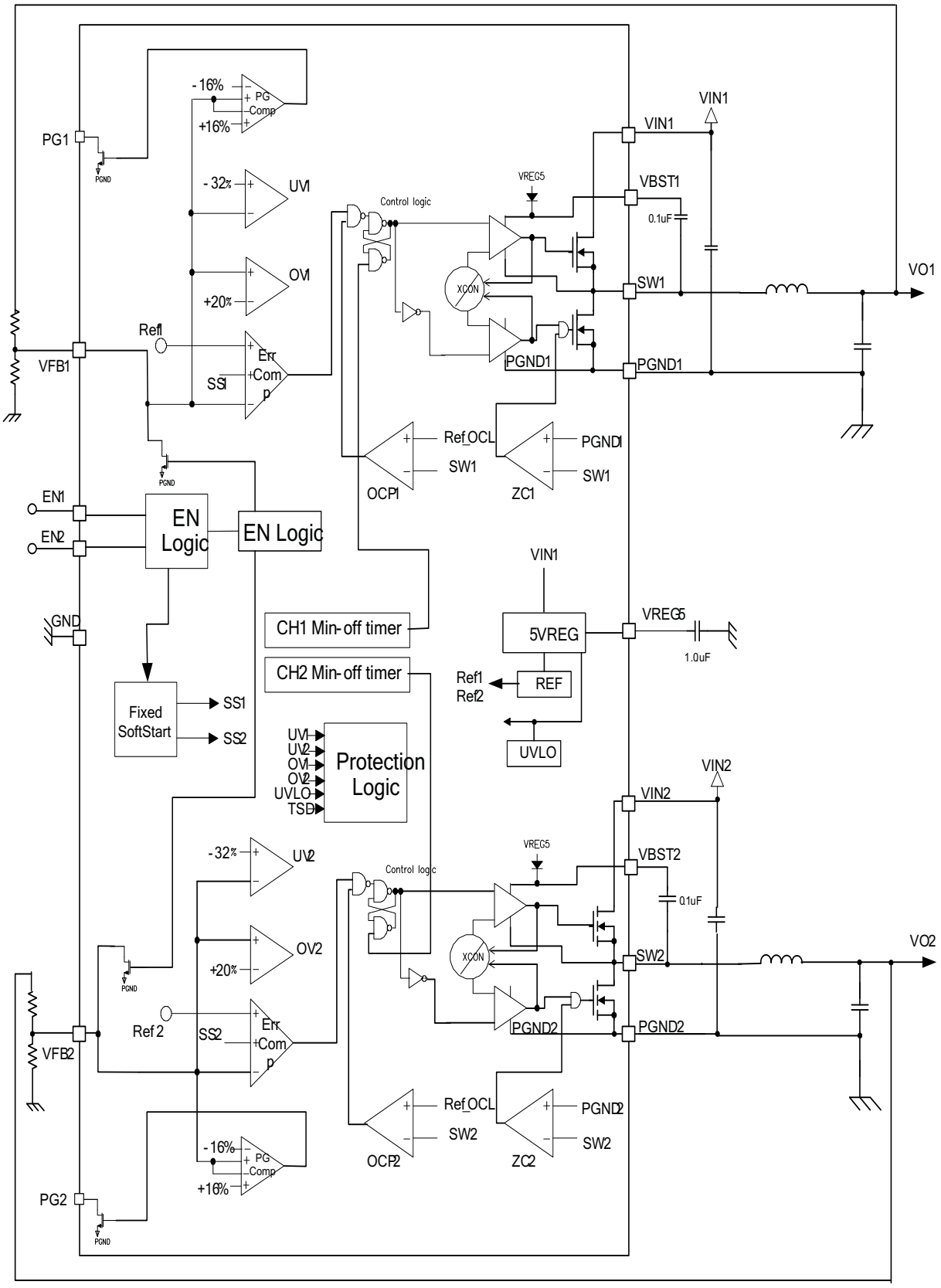


PIN FUNCTIONS(1)

PIN			I/O	DESCRIPTION
NAME	NUMBER			
	PWP	RSA		
VIN1, VIN2	1, 16	3, 2	I	Power inputs and connects to both high side NFET drains. Supply Input for 5.5V linear regulator.
VBST1, VBST2	2, 15	4, 1	I	Supply input for high-side NFET gate drive circuit. Connect 0.1µF ceramic capacitor between VBSTx and SWx pins. An internal diode is connected between VREG5 and VBSTx
SW1, SW2	3, 14	5, 16	I/O	Switch node connections for both the high-side NFETs and low–side NFETs. Input of current comparator.
PGND1, PGND2	4, 13	6, 15	I/O	Ground returns for low-side MOSFETs. Input of current comparator.
EN1, EN2	5, 12	7, 14	I	Enable. Pull High to enable according converter.
PG1, PG2	6, 11	8, 13	O	Open drain power good output. Low means the output voltage of the corresponding output is out of regulation.
VFB1, VFB2	7, 10	9, 12	I	D-CAP2 feedback inputs. Connect to output voltage with resistor divider.
GND	8	10	I/O	Signal GND. Connect sensitive SSx and VFBx returens to GND at a single point.
VREG5	9	11	O	Output of 5.5V linear regulator. Bypass to GND with a high-quality ceramic capacitor of at least 1.0 µF. VREG5 is active when VIN1 is added .
Exposed Thermal Pad	Back side	Back side	I/O	Thermal pad of the package. Must be soldered to achieve appropriate dissipation. Must be connected to GND.

(1) x means either 1 or 2, e.g. VFBx means VFB1 or VFB2.

FUNCTIONAL BLOCK DIAGRAM



OVERVIEW

The TPS54294 is a 2A/2A dual synchronous step-down (buck) converter with two integrated N-channel MOSFETs for each channel. It operates using D-CAP2™ control mode. The fast transient response of D-CAP2™ control reduces the required output capacitance to meet a specific level of performance. Proprietary internal circuitry allows the use of low ESR output capacitors including ceramic and special polymer types.

DETAILED DESCRIPTION

PWM Operation

The main control loop of the TPS54294 is an adaptive on-time pulse width modulation (PWM) controller that supports a proprietary D-CAP2™ control mode. D-CAP2™ control combines constant on-time control with an internal compensation circuit for pseudo-fixed frequency and low external component count configuration with both low ESR and ceramic output capacitors. It is stable even with virtually no ripple at the output.

At the beginning of each cycle, the high-side MOSFET is turned on. This MOSFET is turned off when the internal timer expires. This timer is set by the converter's input voltage, VINx, and the output voltage, VOx, to maintain a pseudo-fixed frequency over the input voltage range hence it is called adaptive on-time control. The timer is reset and the high-side MOSFET is turned on again when the feedback voltage falls below the nominal output voltage. An internal ramp is added to the reference voltage to simulate output voltage ripple, eliminating the need for ESR induced output ripple from D-CAP™ control.

PWM Frequency and Adaptive On-Time Control

TPS54294 uses an adaptive on-time control scheme and does not have a dedicated on board oscillator. The TPS54294 runs with a pseudo-fixed frequency of 700 kHz by using the input voltage and output voltage to set the on-time timer. The on-time is inversely proportional to the input voltage and proportional to the output voltage, therefore, when the duty ratio is VOx/VINx, the frequency is constant.

Auto-Skip Eco-Mode™ Control

The TPS54294 is designed with Auto-Skip Eco-mode™ to increase light load efficiency. As the output current decreases from heavy load condition, the inductor current also reduces and eventually comes to the point where its ripple valley touches the zero level, which is the boundary between continuous conduction and discontinuous conduction modes. The rectifying MOSFET is turned off when zero inductor current is detected. As the load current further decreases the converter runs into discontinuous conduction mode. The on-time is kept almost half as it was in the continuous conduction mode because it takes longer to discharge the output capacitor with smaller load current to the nominal output voltage. The transition point to the light load operation $I_{Ox(LL)}$ current can be estimated with Equation 1with 700-kHz used as f_{SW}.

$$I_{Ox(LL)} = \frac{1}{2 \times L1x \times f_{SW}} \times \frac{(V_{INx} - V_{Ox}) \times V_{Ox}}{V_{INx}} \quad (1)$$

Soft Start and Pre-Biased Soft Start

The TPS54294 has an internal, 1.0ms, soft-start for each channel. When the ENx pin becomes high, an internal DAC begins ramping up the reference voltage to the PWM comparator. Smooth control of the output voltage is maintained during start up.

The TPS54294 contains a unique circuit to prevent current from being pulled from the output during startup if the output is pre-biased. When the soft-start commands a voltage higher than the pre-bias level (internal soft start becomes greater than internal feedback voltage, VFBx), the controller slowly activates synchronous rectification by starting the first low side FET gate driver pulses with a narrow on-time. It then increments that on-time on a cycle-by-cycle basis until it coincides with the time dictated by (1-D), where D is the duty cycle of the converter. This scheme prevents the initial sinking of the pre-biased output, and ensures that the output voltage (VOx) starts and ramps up smoothly into regulation from pre-biased startup to normal mode operation.

POWERGOOD

The TPS54294 has power-good outputs that are measured on VFBx. The power-good function is activated after the soft-start has finished. If the output voltage is within 16% of the target voltage, the internal comparator detects the power good state and the power good signal becomes high after 1.5ms delay. During start-up, this internal delay starts after 1.5ms of the UVP Enable delay time to avoid a glitch of the power-good signal. If the feedback voltage goes outside of ±16% of the target value, the power-good signal becomes low after 2µs.

Over-Current Protection

he output over-current protection (OCP) is implemented using a cycle-by-cycle valley detection control circuit. The switch current is monitored by measuring the low-side FET switch voltage between the SWx and PGNDx pins. This voltage is proportional to the switch current and the on-resistance of the FET. To improve the measurement accuracy, the voltage sensing is temperature compensated.

During the on-time of the high-side FET switch, the switch current increases at a linear rate determined by VINx, VOx, the on-time and the output inductor value. During the on-time of the low-side FET switch, this current decreases linearly. The average value of the switch current is the load current I_{OUTx}. If the sensed voltage on the low-side FET is above the voltage proportional to the current limit, the converter keeps the low-side switch on until the measured voltage falls below the voltage corresponding to the current limit and a new switching cycle begins. In subsequent switching cycles, the on-time is set to the value determined for CCM and the current is monitored in the same manner.

Following are some important considerations for this type of over-current protection. The load current is one half of the peak-to-peak inductor current higher than the over-current threshold. Also when the current is being limited, the output voltage tends to fall as the demanded load current may be higher than the current available from the converter. When the over current condition is removed, the output voltage returns to the regulated value. This protection is non-latching.

Over/Under Voltage Protection

TPS54294 monitors the resistor divided feedback voltage to detect over and under voltage. If the feedback voltage is higher than 120% of the reference voltage, the OVP comparator output goes high and the circuit latches both the high-side MOSFET driver and the low-side MOSFET driver off. When the feedback voltage is lower than 68% of the reference voltage, the UVP comparator output goes high and an internal UVP delay counter begins counting. After 1.5ms, TPS54294 latches OFF both the high-side MOSFET and the low-side MOSFET drivers. This function is enabled approximately 1.7 times the softstart time after power-on. The OVP and UVP latch off is reset when EN is toggled.

UVLO Protection

Under-voltage lock out protection (UVLO) monitors the voltage of the V_{REG5} pin. When the V_{REG5} voltage is lower than the UVLO threshold, the TPS54294 shuts down. As soon as the voltage increases above the UVLO threshold, the converter starts again.

Thermal Shutdown

TPS54294 monitors its temperature. If the temperature exceeds the threshold value (typically 155°C), the device shuts down. When the temperature falls below the threshold, the IC starts again.

When VIN1 starts up and VREG5 output voltage is below its nominal value, the thermal shutdown threshold is lower than 155°C. As long as VIN1 rises, T_J must be kept below 110°C.

TYPICAL CHARACTERISTICS

One output is enabled unless otherwise noted. VI = VIN1 or VIN2.
VIN = 12 V, T_A = 25°C (unless otherwise noted).

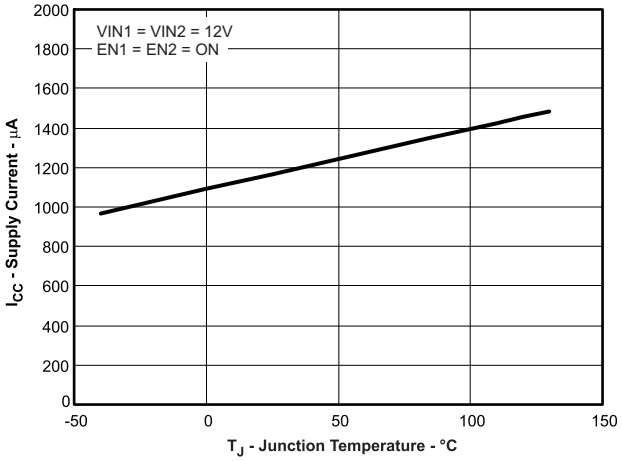


Figure 1. Input Current vs Junction Temperature

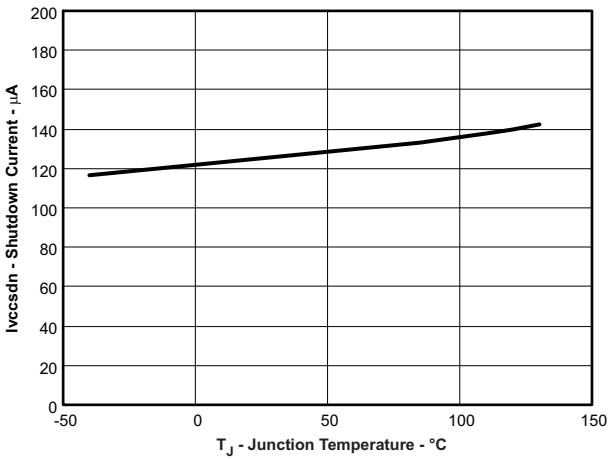


Figure 2. Input Shutdown Current vs Junction Temperature

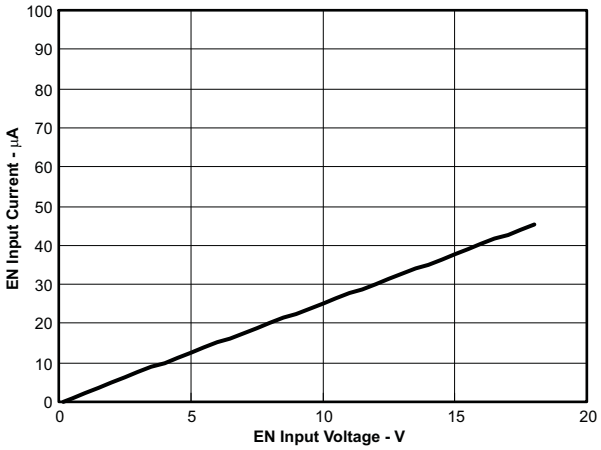


Figure 3. EN Current vs EN Voltage (VEN=12V)

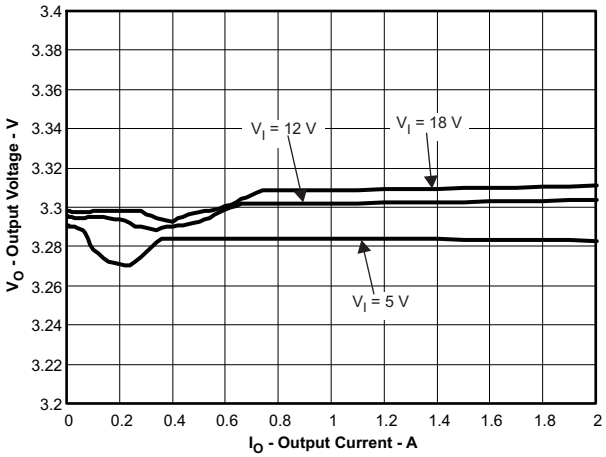


Figure 4. VO1=3.3V Output Voltage vs Output Current

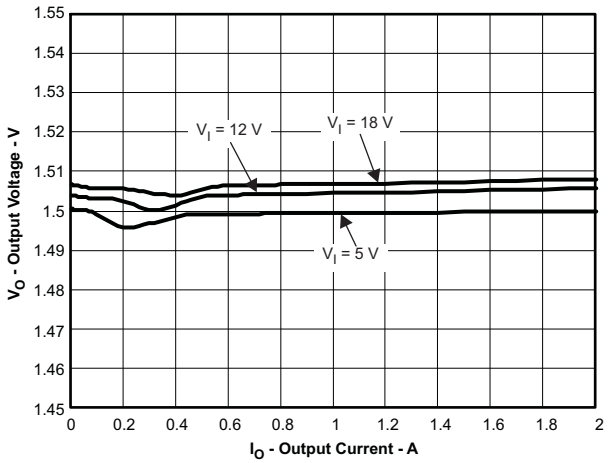


Figure 5. VO2=1.5V Output Voltage vs Output Current

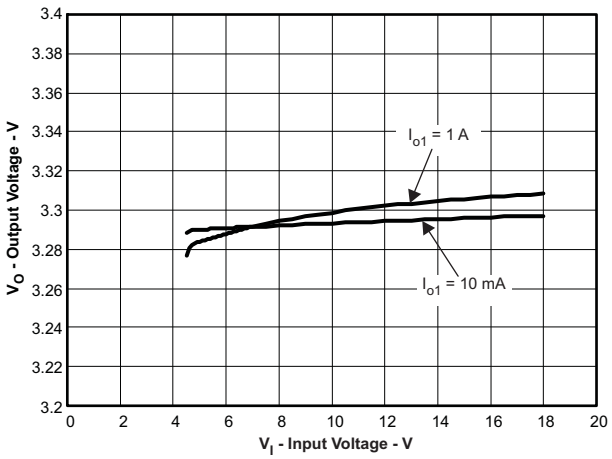


Figure 6. VO1=3.3V Output Voltage vs Input Voltage

TYPICAL CHARACTERISTICS

One output is enabled unless otherwise noted. VI = VIN1 or VIN2.
VIN = 12 V, T_A = 25°C (unless otherwise noted).

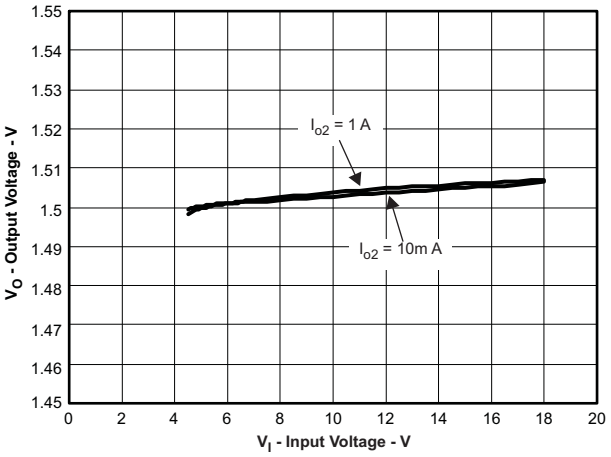


Figure 7. VO2=1.5V Output Voltage vs Input Voltage

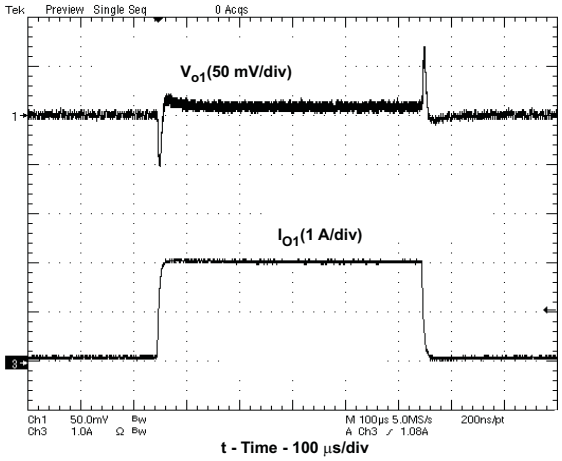


Figure 8. VO1=3.3V, 0A to 2A Load Transient Response

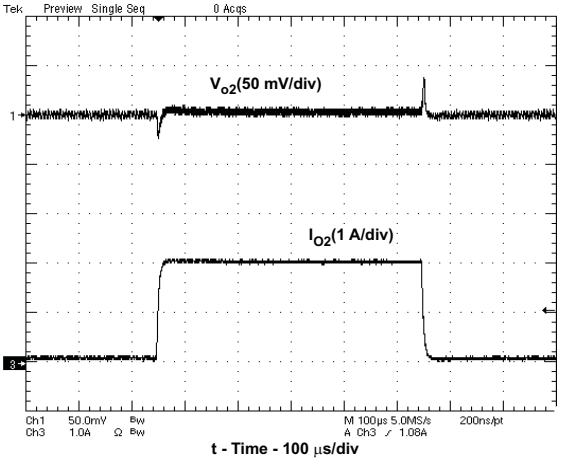


Figure 9. VO2=1.5V, 0A to 2A Load Transient Response

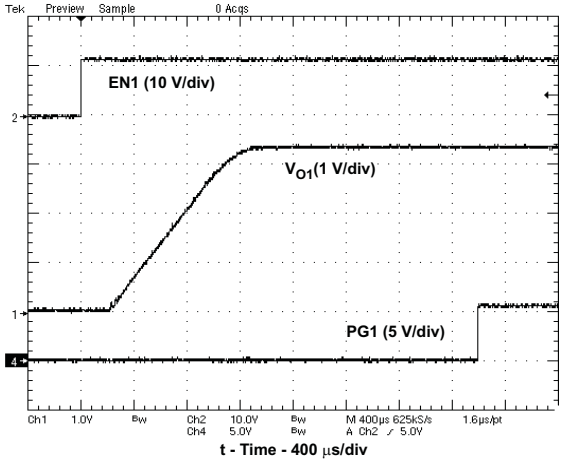


Figure 10. VO1=3.3V, SoftStart and Powergood

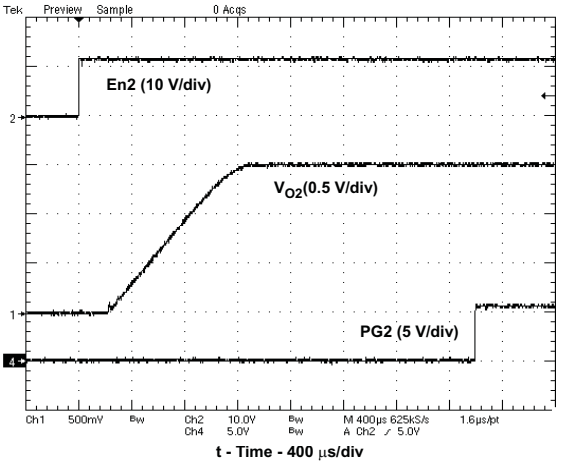


Figure 11. VO2=1.5V, SoftStart and Power Good

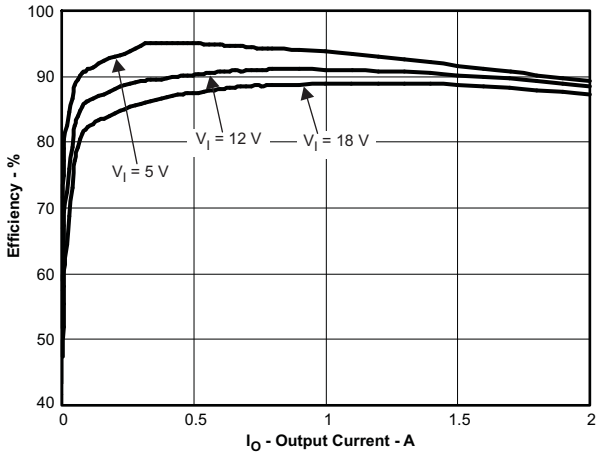


Figure 12. VO1=3.3V, Efficiency vs Output Current

TYPICAL CHARACTERISTICS

One output is enabled unless otherwise noted. VI = VIN1 or VIN2.
VIN = 12 V, T_A = 25°C (unless otherwise noted).

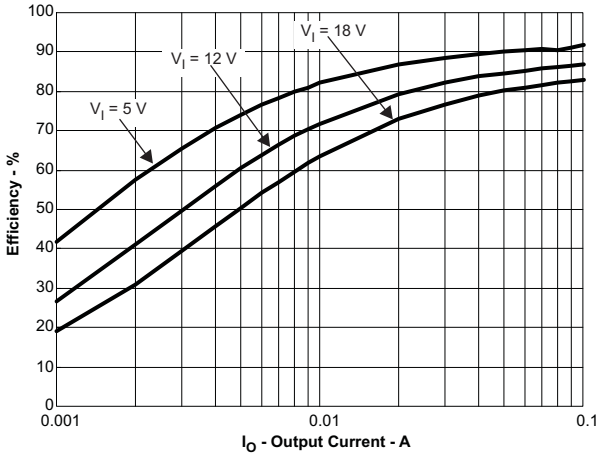


Figure 13. VO1=3.3V, Efficiency vs Output Current

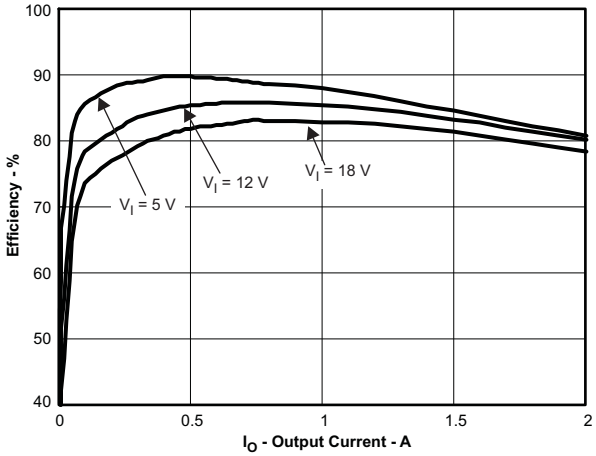


Figure 14. VO1=1.5V, Efficiency vs Output Current

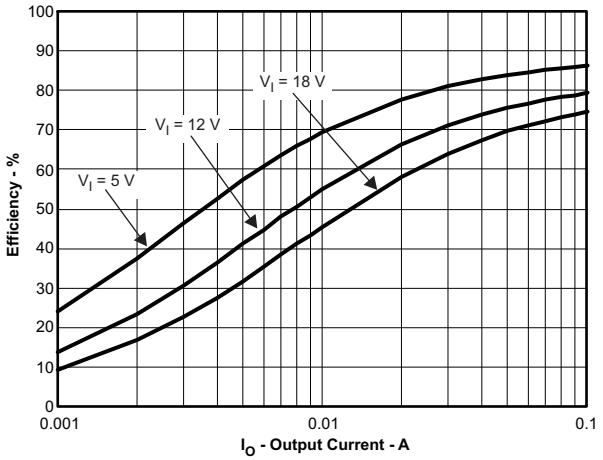


Figure 15. VO2=1.5V, Efficiency vs Output Current

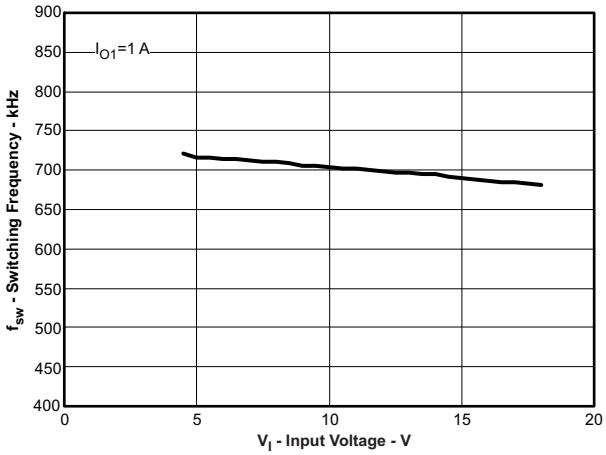


Figure 16. VO1=3.3V, SW-frequency vs Input Voltage

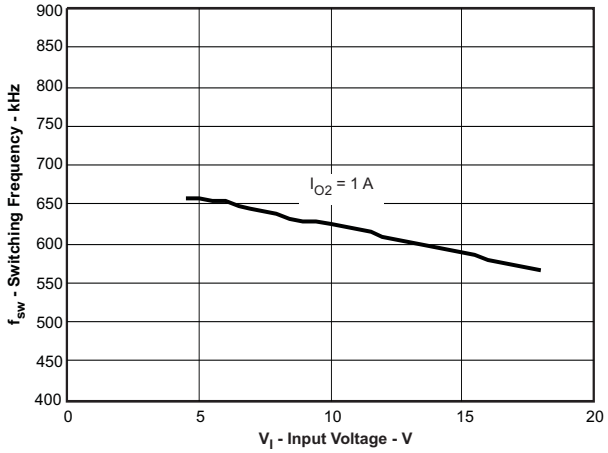


Figure 17. VO2=1.5V, SW-frequency vs Input Voltage

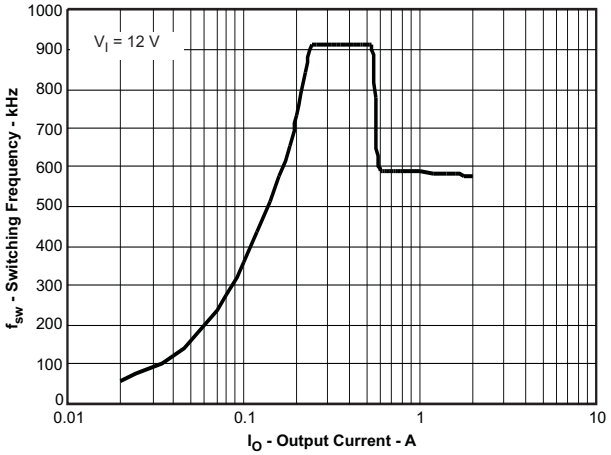


Figure 18. VO1=3.3V, SW-frequency vs Output Current

TYPICAL CHARACTERISTICS

One output is enabled unless otherwise noted. VI = VIN1 or VIN2.
VIN = 12 V, T_A = 25°C (unless otherwise noted).

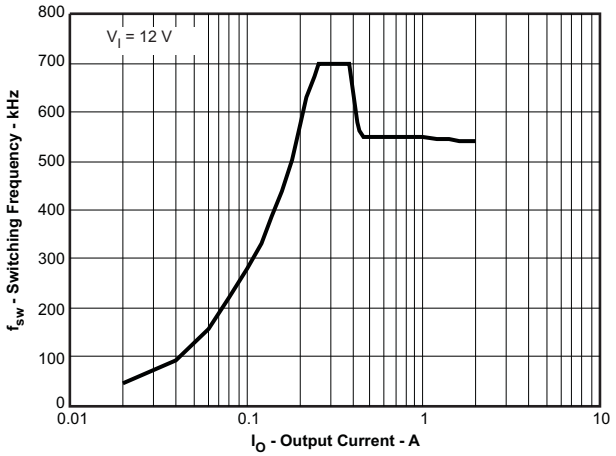


Figure 19. VO2=1.5V, SW-frequency vs Output Current

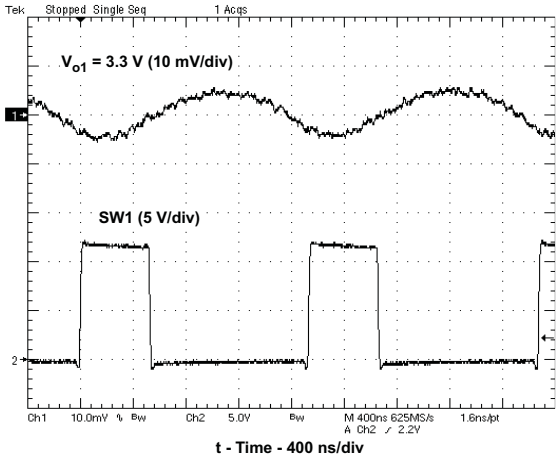


Figure 20. VO1=3.3V, VO1 Ripple Voltage (I_{O1}=2A)

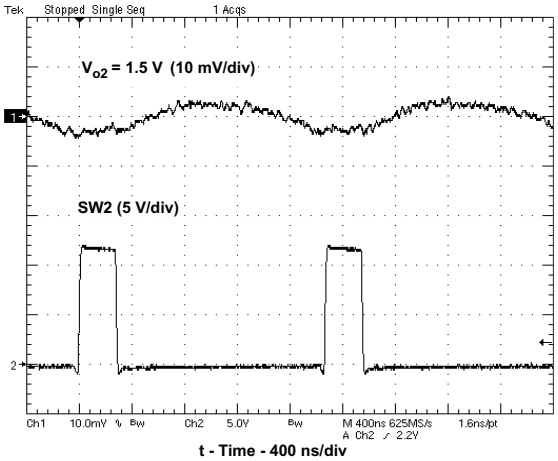


Figure 21. VO2=1.5V, Ripple Voltage (I_{O2}=2A)

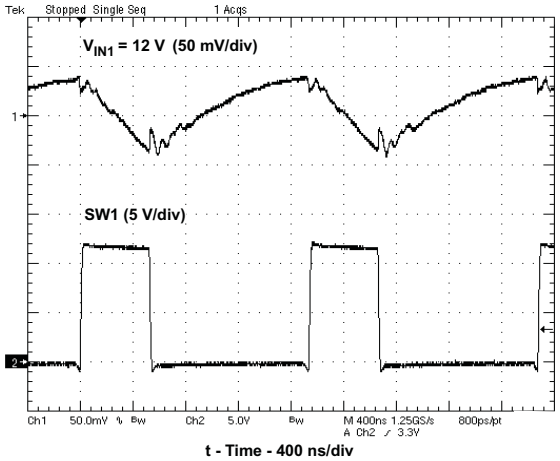


Figure 22. VIN1 Input Voltage Ripple (I_{O1}=2A)

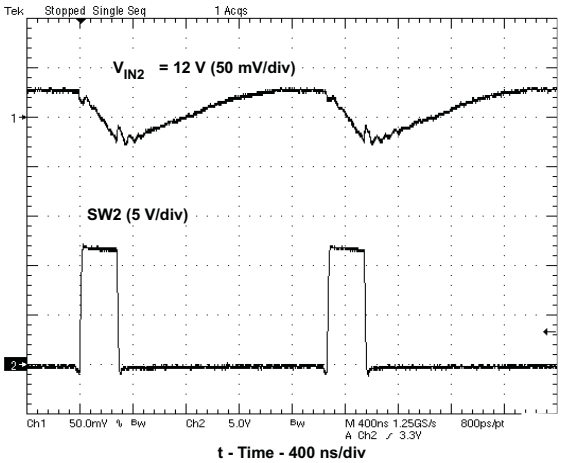


Figure 23. VIN2 INPUT VOLTAGE RIPPLE (I_{O2}=2A)

DESIGN GUIDE

Step By Step Design Procedure

To begin the design process, you must know a few application parameters:

- Input voltage range
- Output voltage
- Output current

In all formulas x is used to indicate that they are valid for both converters. For the calculations the estimated switching frequency of 700 kHz is used.

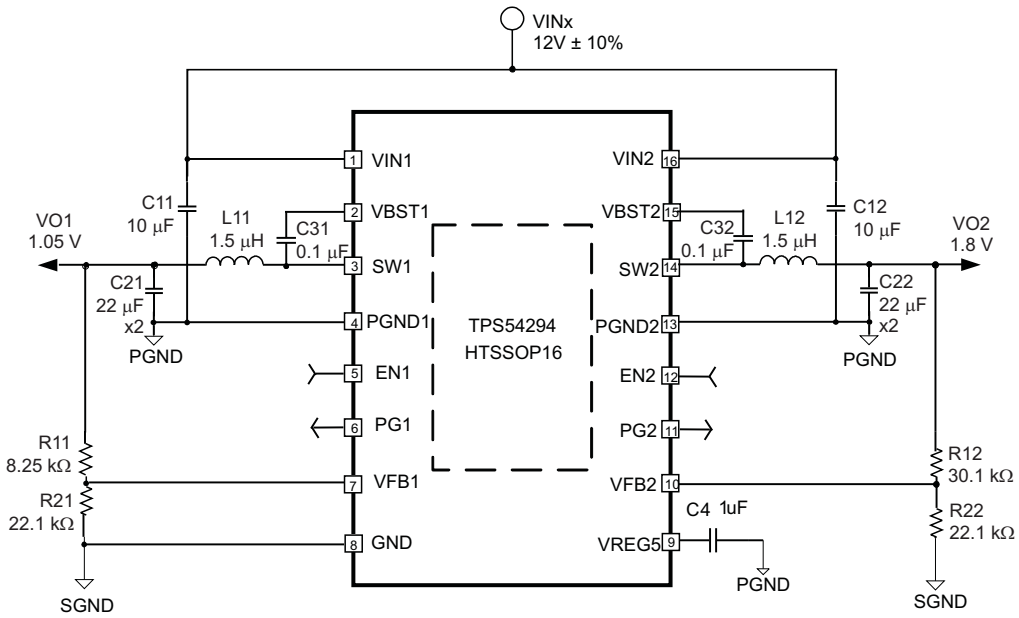


Figure 24. Schematic Diagram for the Design Example

Output Voltage Resistors Selection

The output voltage is set with a resistor divider from the output node to the VFBx pin. It is recommended to use 1% tolerance or better divider resistors. Start by using Equation 2 to calculate V_{Ox}.

To improve the efficiency at very light loads consider using larger value resistors, but too high resistance values will be more susceptible to noise and voltage errors due to the VFBx input current will be more noticeable.

$$V_{Ox} = 0.765\ V \times \left(1 + \frac{R1x}{R2x}\right) \quad (2)$$

Output Filter Selection

The output filter used with the TPS54294 is an LC circuit. This LC filter has double pole at:

$$F_P = \frac{1}{2\pi \sqrt{L_{OUT} \times C_{OUT}}} \quad (3)$$

At low frequencies, the overall loop gain is set by the output set-point resistor divider network and the internal gain of the TPS545294. The low frequency phase is 180 degrees. At the output filter pole frequency, the gain rolls off at a –40 dB per decade rate and the phase drops rapidly. D-CAP2™ introduces a high frequency zero that reduces the gain roll off to –20 dB per decade and increases the phase to 90 degrees one decade above the zero frequency. The inductor and capacitor selected for the output filter must be selected so that the double pole of Equation 3 is located below the high frequency zero but close enough that the phase boost provided by the high frequency zero provides adequate phase margin for a stable circuit. To meet this requirement use the values recommended in Table 1.

Table 1. Recommended Component Values

OUTPUT VOLTAGE (V)	R1x (kΩ)	R2x (kΩ)	Cffx (pF)	L1x (µH)	C2x (µF)
1	6.81	22.1		1.0-1.5	22 - 68
1.05	8.25	22.1		1.0-1.5	22 - 68
1.2	12.7	22.1		1.0-1.5	22 - 68
1.5	21.5	22.1		1.5	22 - 68
1.8	30.1	22.1	5 - 22	1.5	22 - 68
2.5	49.9	22.1	5 - 22	2.2	22 - 68
3.3	73.2	22.1	5 - 22	2.2	22 - 68
5	124	22.1	5 - 22	3.3	22 - 68

For higher output voltages at or above 1.8 V, additional phase boost can be achieved by adding a feed forward capacitor (Cff) in parallel with R1.

The inductor peak-to-peak ripple current, peak current and RMS current are calculated using Equation 4, Equation 5 and Equation 6. The inductor saturation current rating must be greater than the calculated peak current and the RMS or heating current rating must be greater than the calculated RMS current.

For the calculations, use 700 kHz as the switching frequency, f_{SW}. Make sure the chosen inductor is rated for the peak current of Equation 5 and the RMS current of Equation 6.

$$\Delta I_{L1x} = \frac{V_{Ox}}{V_{INx(MAX)}} \times \frac{V_{INx(MAX)} - V_{Ox}}{L1x \times f_{SW}} \quad (4)$$

$$I_{Lpeakx} = I_{Ox} + \frac{\Delta I_L}{2} \quad (5)$$

$$I_{LOx(RMS)} = \sqrt{I_{Ox}^2 + \frac{1}{12}\Delta I_L^2} \quad (6)$$

For the above design example, the calculated peak current is 2.46 A and the calculated RMS current is 2.02 A for VO1. The inductor used is a TDK CLF7045-1R5N with a rated current of 7.3A based on the inductance change and of 4.9A based on the temperature rise.

The capacitor value and ESR determines the amount of output voltage ripple. The TPS54294 is intended for use with ceramic or other low ESR capacitors. The recommended value range is from 22µF to 68µF. Use Equation 7 to determine the required RMS current rating for the output capacitor(s).

$$I_{COx(RMS)} = \frac{V_{Ox} \times (V_{INx} - V_{Ox})}{\sqrt{12} \times V_{INx} \times L_{Ox} \times f_{SW}} \quad (7)$$

For this design two TDK C3216X5R0J226M 22µF output capacitors are used. The typical ESR is 2 mΩ each. The calculated RMS current is 0.19A and each output capacitor is rated for 4A.

Input Capacitor Selection

The TPS54294 requires an input decoupling capacitor and a bulk capacitor is needed depending on the application. A ceramic capacitor of or above 10µF is recommended for the decoupling capacitor. Additionally, 0.1 µF ceramic capacitors from pin 1 and Pin 16 to ground are recommended to improve the stability and reduce the SWx node overshoots. The capacitors voltage rating needs to be greater than the maximum input voltage.

Bootstrap Capacitor Selection

A 0.1 µF ceramic capacitors must be connected between the VBSTx and SWx pins for proper operation. It is recommended to use ceramic capacitors with a dielectric of X5R or better.

VREG5 Capacitor Selection

A 1 µF ceramic capacitor must be connected between the VREG5 and GND pins for proper operation. It is recommended to use a ceramic capacitor with a dielectric of X5R or better.

Thermal Information

This 16-pin PWP package incorporates an exposed thermal pad. The thermal pad must be soldered directly to the printed circuit board (PCB). After soldering, the PCB is used as a heatsink. In addition, through the use of thermal vias, the thermal pad can be attached directly to the appropriate copper plane shown in the electrical schematic for the device, or alternatively, can be attached to a special heatsink structure designed into the PCB. This design optimizes the heat transfer from the integrated circuit (IC).

For additional information on the exposed thermal pad and how to use the advantage of its heat dissipating abilities, refer to the Technical Brief, *PowerPAD™ Thermally Enhanced Package*, Texas Instruments Literature No. SLMA002 and Application Brief, *PowerPAD™ Made Easy*, Texas Instruments Literature No. SLMA004.

The exposed thermal pad dimensions for this package are shown in the following illustration.

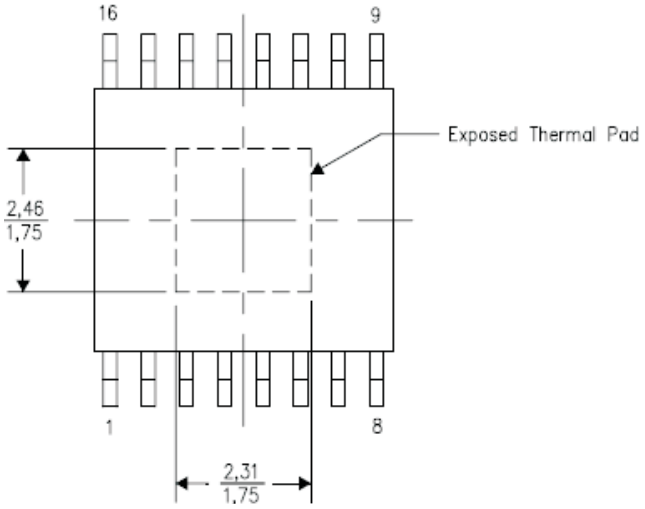
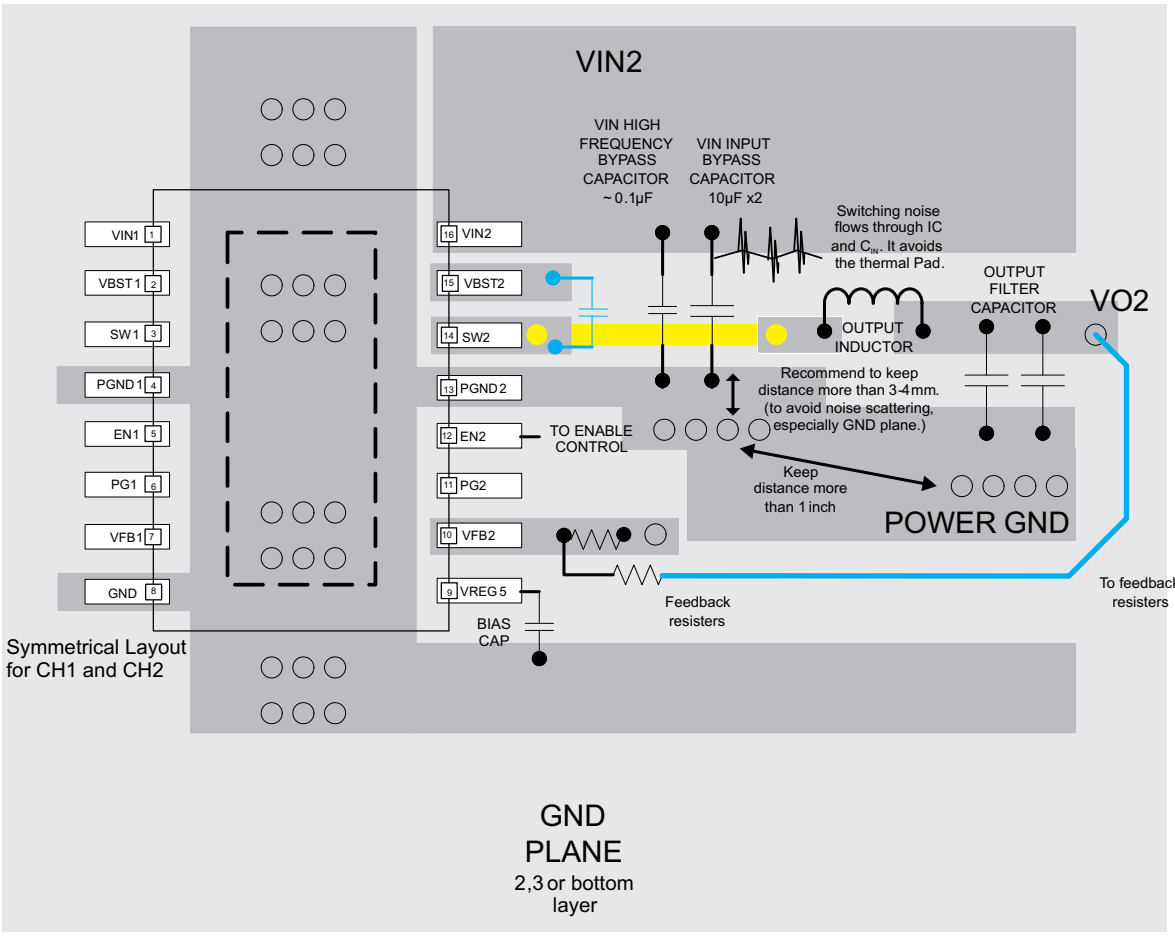


Figure 25. Thermal Pad Dimensions

Layout Considerations

1. Keep the input current loop as small as possible. And avoid the input switching current through the thermal pad.
2. Keep the SW node as physically small and short as possible to minimize parasitic capacitance and inductance and to minimize radiated emissions.
3. Keep analog and non-switching components away from switching components.
4. Make a single point connection from the signal ground to power ground.
5. Do not allow switching currents to flow under the device.
6. Keep the pattern lines for VINx and PGNDx broad.
7. Exposed pad of device must be soldered to PGND.
8. VREG5 capacitor should be placed near the device, and connected to GND.
9. Output capacitors should be connected with a broad pattern to the PGND.
10. Voltage feedback loops should be as short as possible, and preferably with ground shields.
11. Kelvin connections should be brought from the output to the feedback pin of the device.
12. Providing sufficient vias is preferable for VIN, SW and PGND connections.
13. PCB pattern for VIN, SW, and PGND should be as broad as possible.
14. VIN Capacitor should be placed as near as possible to the device.



○ **Via to GND Plane**

- Blue parts can be placed on the bottom side

- Connect the SWx pins through another layer with the inductor (yellow line)

Figure 26. TPS54294 Layout

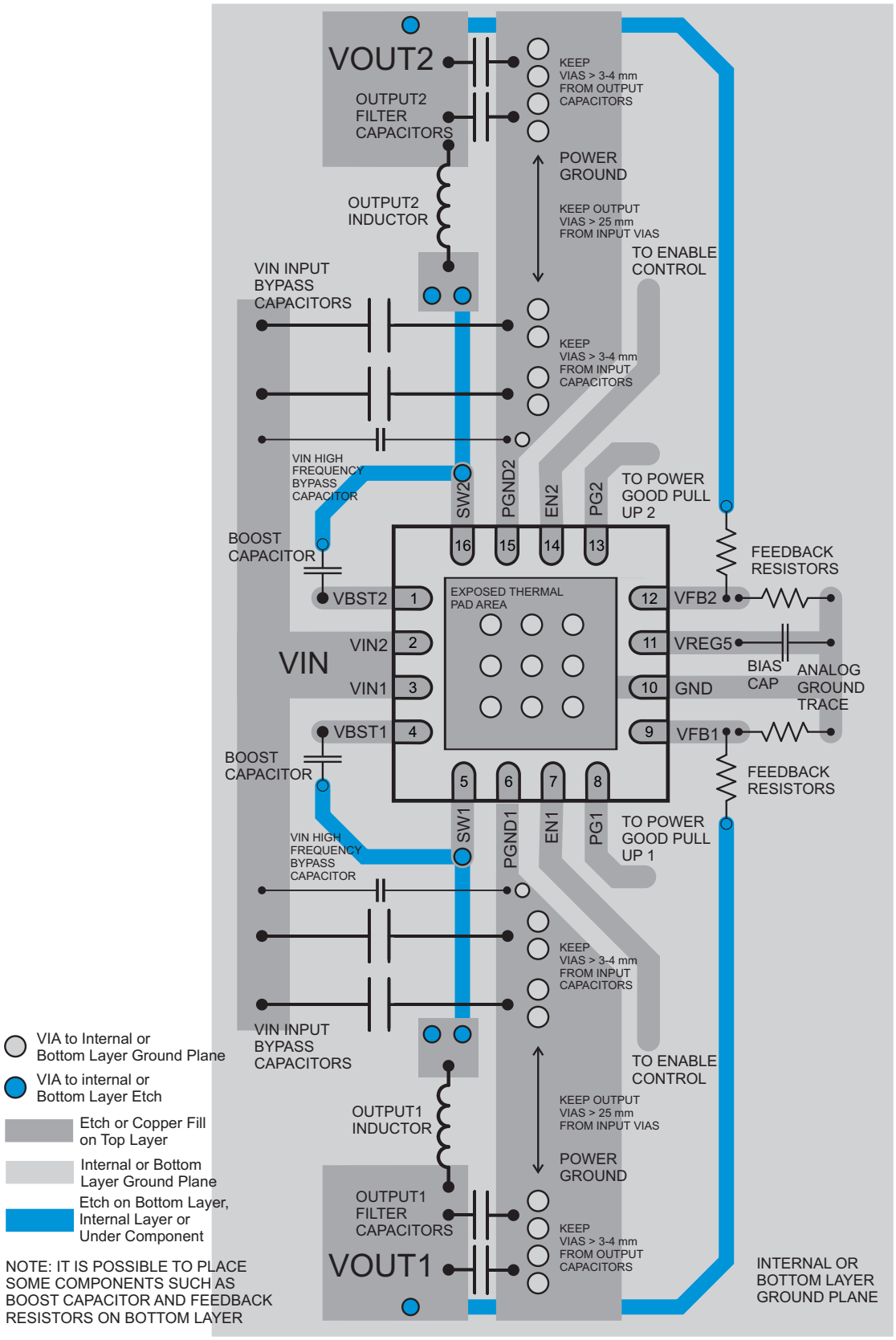


Figure 27. TPS54294 RSA Package Layout

REVISION HISTORY

NOTE: Page numbers of current version may differ from previous versions.

Changes from Original (October 2011) to Revision A — **Page**

- Added input voltage range for VFB1, VFB2 to Absolute Maximum Ratings 2
- Added input voltage range for VFB1, VFB2 to Recommended Operating Conditions 3
- Added indication for not production tested parameters. 3
- Added indication for not production tested parameters. 4
- Added Over/Under Voltage Protection Description 8

Changes from Revision A (November 2011) to Revision B — **Page**

- Deleted V_{REG5} MIN and MAX values 3
- Deleted Line and Load regulation specs from VREG5 specification 3
- Added "Specified by design. Not production tested" annotation to MOSFETs specification 3
- Deleted MIN and MAX values from V_{UVREG5} specification 4

Changes from Revision B (December 2011) to Revision C — **Page**

- Removed (SWIFT™) from the data sheet title 1
- Added 16-pin VQFN package to Features and Description 1
- Added RSA pinout image, pin names and functions to Device Info Section 5
- Changed TPS54295, 2 places to TPS54294 in Over/Under Voltage protection section 8
- Added RSA-package board layout, ... 18

Changes from Revision C (April 2013) to Revision D — **Page**

- Deleted T_A = 25°C from the ELECTRICAL CHARACTERISTICS Conditions column 3
- Changed VIN supply current Max value From: 2000 µA To: 2500 µA 3
- Changed VIN shutdown current Max value From: 150 µA To: 200 µA 3

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead finish/ Ball material (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
TPS54294PWP	ACTIVE	HTSSOP	PWP	16	90	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	PS54294	Samples
TPS54294PWPR	ACTIVE	HTSSOP	PWP	16	2000	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	PS54294	Samples
TPS54294RSAR	ACTIVE	QFN	RSA	16	3000	RoHS & Green	NIPDAU	Level-1-260C-UNLIM	-40 to 85	TPS 54294	Samples
TPS54294RSAT	ACTIVE	QFN	RSA	16	250	RoHS & Green	NIPDAU	Level-1-260C-UNLIM	-40 to 85	TPS 54294	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".
RoHS Exempt: TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.
Green: TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

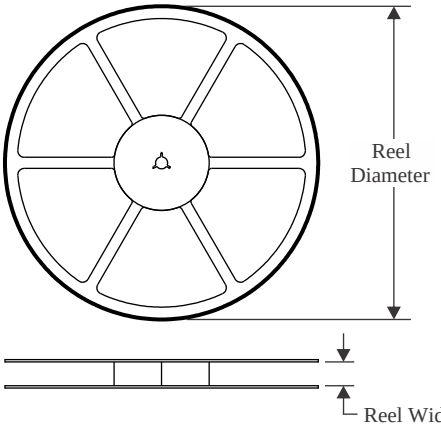
(6) Lead finish/Ball material - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals.
TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

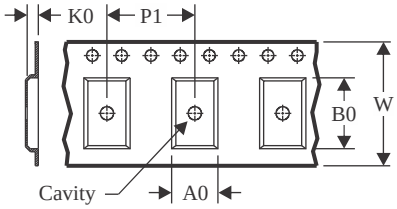
In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

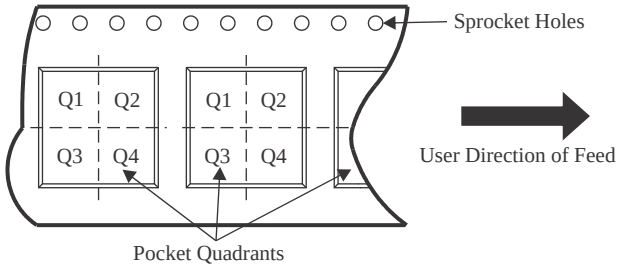


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

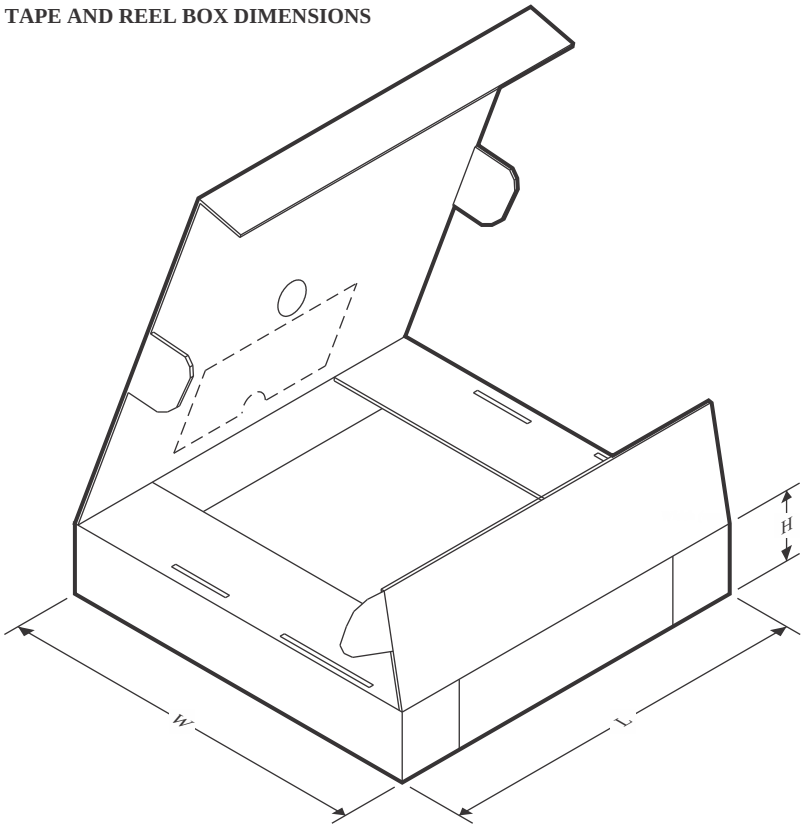
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*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
TPS54294PWPR	HTSSOP	PWP	16	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1
TPS54294RSAR	QFN	RSA	16	3000	330.0	12.4	4.25	4.25	1.15	8.0	12.0	Q2
TPS54294RSAT	QFN	RSA	16	250	180.0	12.4	4.25	4.25	1.15	8.0	12.0	Q2

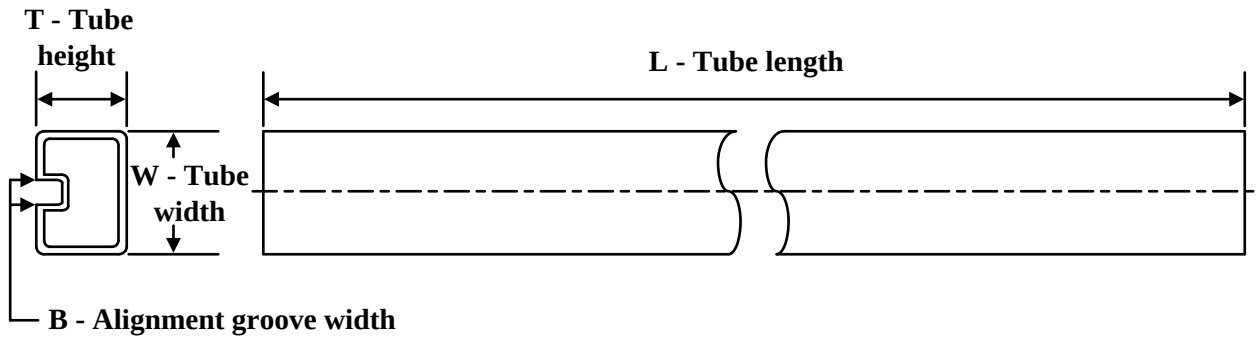
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
TPS54294PWPR	HTSSOP	PWP	16	2000	356.0	356.0	35.0
TPS54294RSAR	QFN	RSA	16	3000	346.0	346.0	33.0
TPS54294RSAT	QFN	RSA	16	250	182.0	182.0	20.0

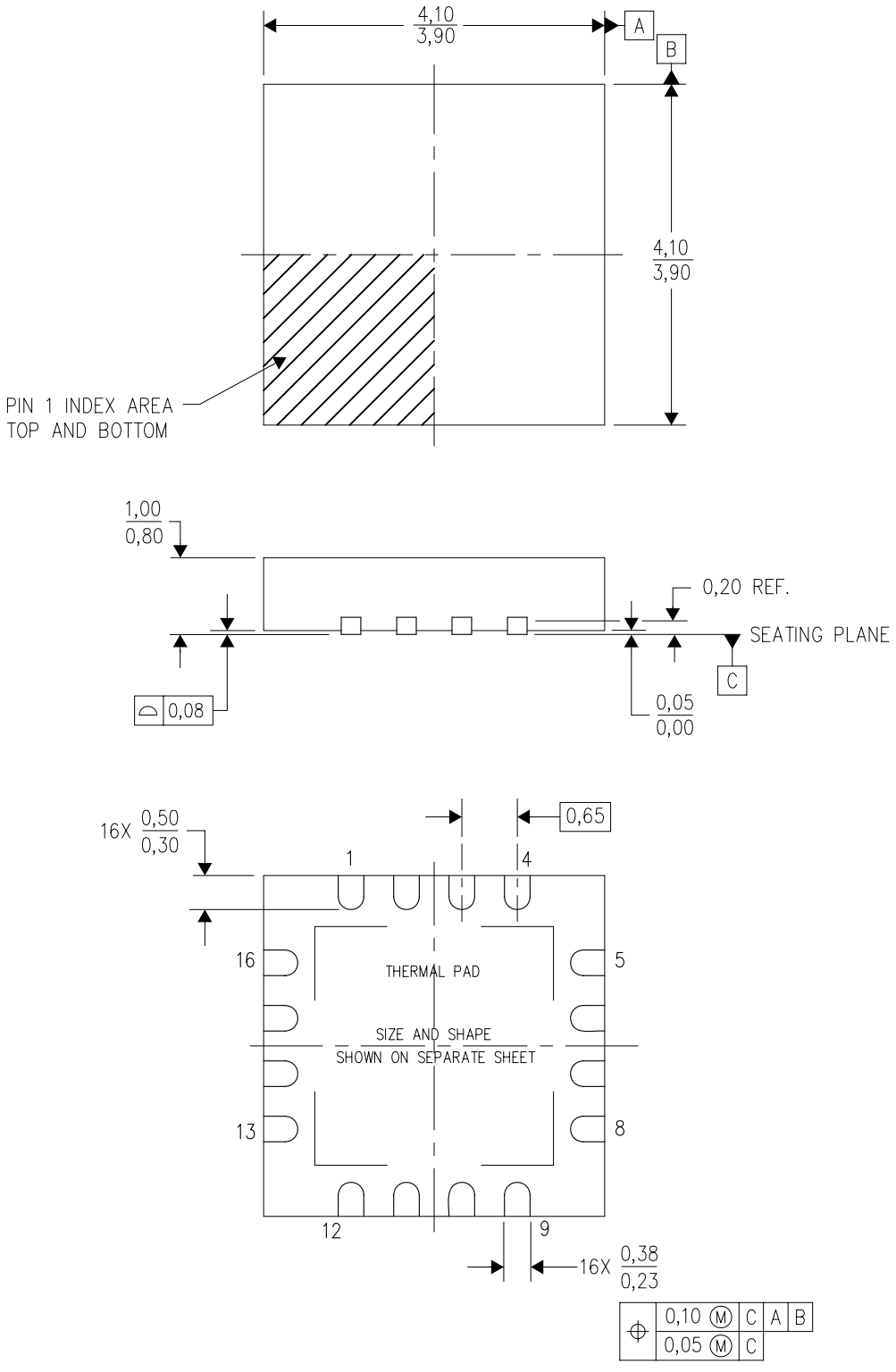
TUBE



*All dimensions are nominal

Device	Package Name	Package Type	Pins	SPQ	L (mm)	W (mm)	T (µm)	B (mm)
TPS54294PWP	PWP	HTSSOP	16	90	530	10.2	3600	3.5
TPS54294PWP	PWP	HTSSOP	16	90	530	10.2	3600	3.5

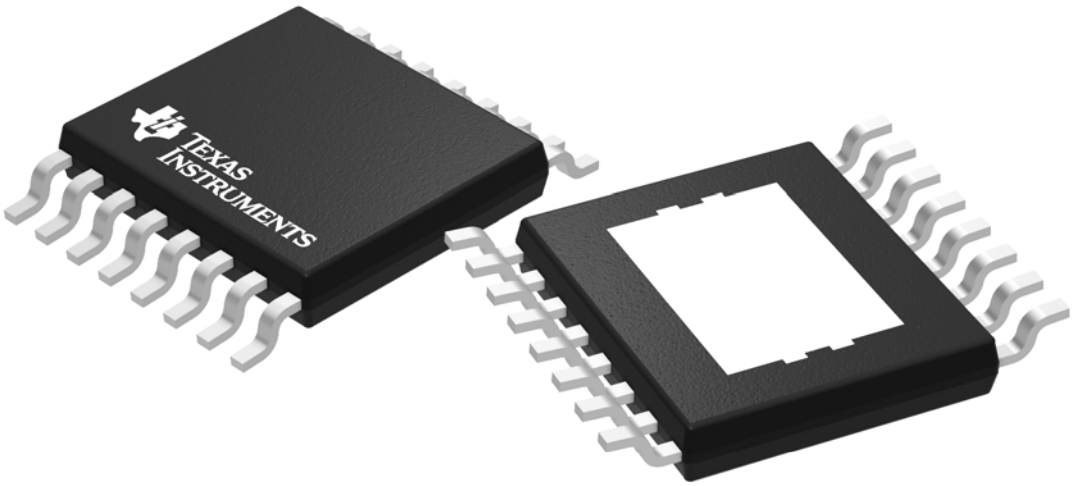
RSA (S–PVQFN–N16) PLASTIC QUAD FLATPACK NO–LEAD



NOTES:
A. All linear dimensions are in millimeters. Dimensioning and tolerancing per ASME Y14.5M–1994.
B. This drawing is subject to change without notice.
C. Quad Flatpack, No–leads (QFN) package configuration.
D. The package thermal pad must be soldered to the board for thermal and mechanical performance.
E. See the additional figure in the Product Data Sheet for details regarding the exposed thermal pad features and dimensions.
F. Falls within JEDEC MO–220.

PWP 16 PowerPAD™ TSSOP - 1.2 mm max height

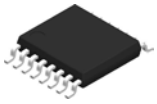
PLASTIC SMALL OUTLINE



Images above are just a representation of the package family, actual package may vary.
Refer to the product data sheet for package details.

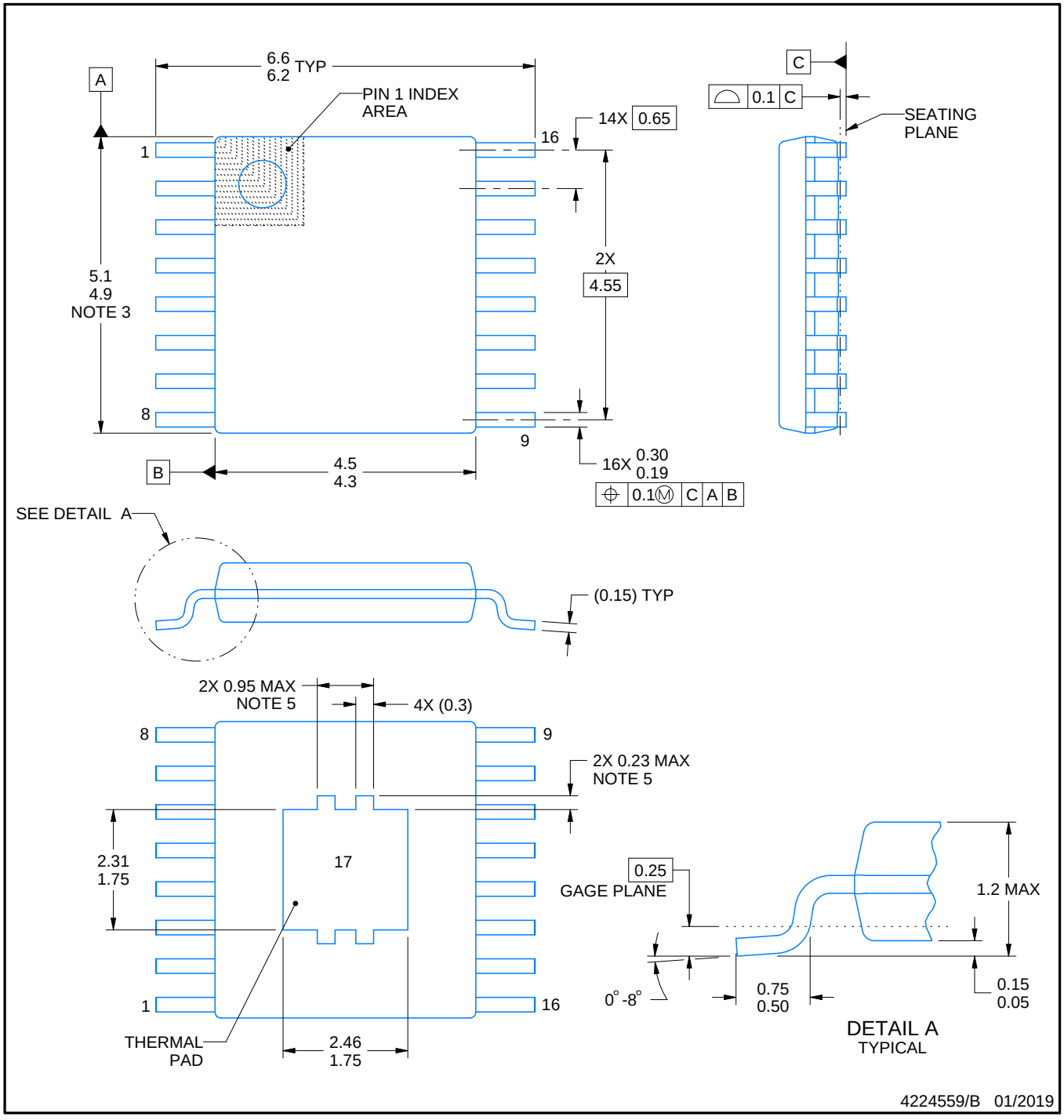
PACKAGE OUTLINE

PWP0016C



PowerPAD™ TSSOP - 1.2 mm max height

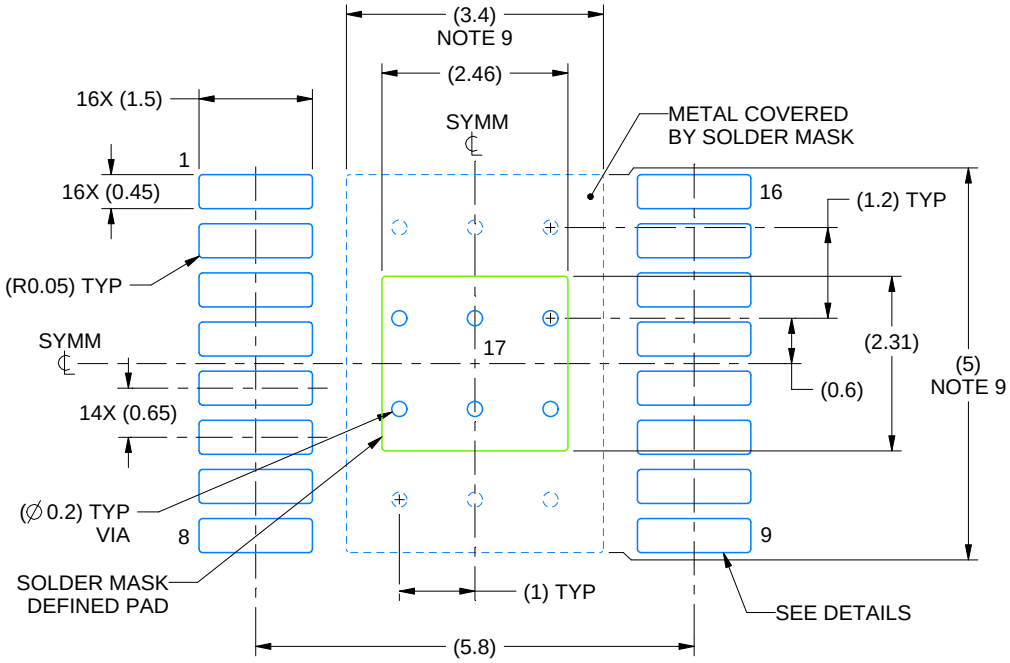
SMALL OUTLINE PACKAGE



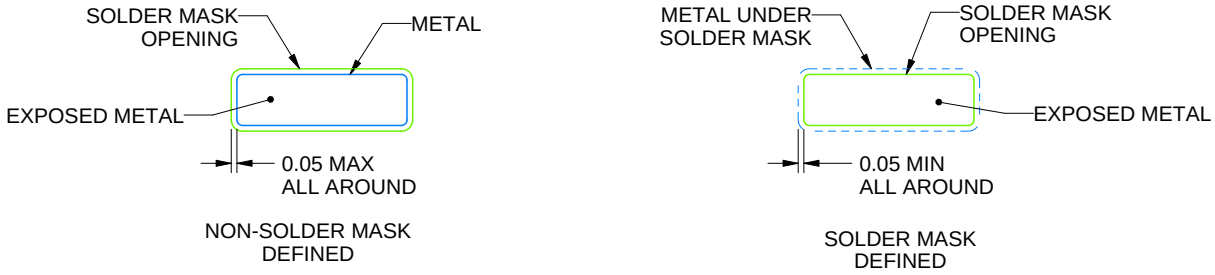
PowerPAD is a trademark of Texas Instruments.

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. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. Reference JEDEC registration MO-153.
5. Features may differ or may not be present.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 10X

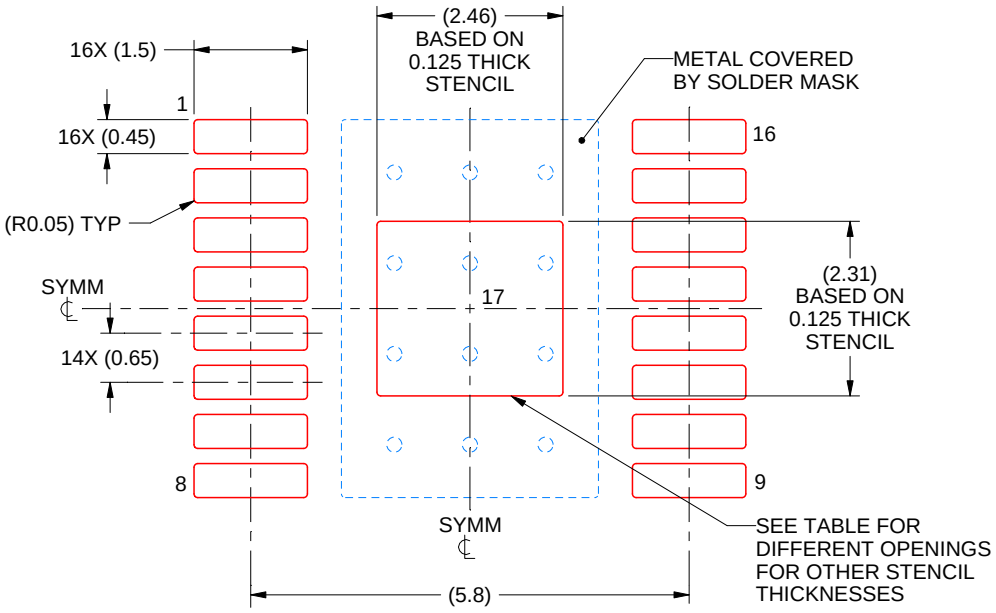


SOLDER MASK DETAILS

4224559/B 01/2019

NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.
8. This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature numbers SLMA002 (www.ti.com/lit/slma002) and SLMA004 (www.ti.com/lit/slma004).
9. Size of metal pad may vary due to creepage requirement.
10. Vias are optional depending on application, refer to device data sheet. It is recommended that vias under paste be filled, plugged or tented.



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE: 10X

STENCIL THICKNESS	SOLDER STENCIL OPENING
0.1	2.75 X 2.58
0.125	2.46 X 2.31 (SHOWN)
0.15	2.25 X 2.11
0.175	2.08 X 1.95

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NOTES: (continued)

11. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
12. Board assembly site may have different recommendations for stencil design.

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