Data Sheet

LT8645SA/LT8646SA

65V, 8A Synchronous Step-Down Silent Switcher 2 with 2.5µA Quiescent Current

FEATURES

- **Silent Switcher®2 Architecture**
  - **Ultralow EMI Emissions on Any PCB**
  - **Eliminates PCB Layout Sensitivity**
  - **Internal Bypass Capacitors Reduce Radiated EMI**
  - **Optional Spread Spectrum Modulation**
- **High Efficiency at High Frequency**
  - **Up to 94% Efficiency at 400kHz, $24V_{IN}$ to $5V_{OUT}$**
  - **Up to 93% Efficiency at 1MHz, $24V_{IN}$ to $5V_{OUT}$**
- **Wide Input Voltage Range: 3.4V to 65V**
- **Wide Output Voltage Range: 0.97V to (V_{IN} - 0.5V)**
- **Ultralow Quiescent Current Burst Mode Operation**
  - **2.5µA I_Q Regulating $12V_{IN}$ to $3.3V_{OUT}$ (LT8645SA)**
  - **Output Ripple < $10mV_{P-P}$**
- **External Compensation: Fast Transient Response and Current Sharing (LT8646SA)**
- **Robust High V_{OUT} Operation**
  - **Safely Tolerates High Reverse Current**
- Fast Minimum Switch On-Time: 40ns
- Low Dropout Under All Conditions: 60mV at 1A
- Adjustable and Synchronizable: 200kHz to 2.2MHz
- Output Soft-Start and Tracking
- Small 32-Lead 6mm × 4mm LQFN Package
- AEC-Q100 Qualified for Automotive Applications

APPLICATIONS

- Automotive and Industrial Supplies
- General Purpose Step-Down

GENERAL DESCRIPTION

The **LT®8645SA/LT8646SA** synchronous step-down regulator features second generation Silent Switcher architecture designed to minimize EMI emissions while delivering high efficiency at high switching frequencies. This includes the integration of bypass capacitors to optimize all the fast current loops inside and make it easy to achieve advertised EMI performance by eliminating layout sensitivity.

The fast, clean, low-overshoot switching edges enable high efficiency operation even at high switching frequencies, leading to a small overall solution size. Peak current mode control with a 40ns minimum on-time allows high step-down ratios even at high switching frequencies. The LT8646SA has external compensation to enable current sharing and fast transient response at high switching frequencies.

Burst Mode® operation enables ultralow standby current consumption, forced continuous mode can control frequency harmonics across the entire output load range, or spread spectrum operation can further reduce EMI emissions.

	V_C COMP	SYNC/ MODE ≠ 0V	CLKOUT PHASE	INTERNAL CAPS	MAX TEMP	HIGH V_{OUT}
LT8645SA	Internal	FCM	180°	Yes	125°C	Yes
LT8646SA	External	FCM	180°	Yes	125°C	Yes
LT8645S	Internal	Pulse-Skip	0°	Yes	125°C	No
LT8646S	External	Pulse-Skip	0°	Yes	125°C	No
LT8645S-2	Internal	Pulse-Skip	0°	No	150°C	No

SIMPLIFIED APPLICATION DIAGRAM

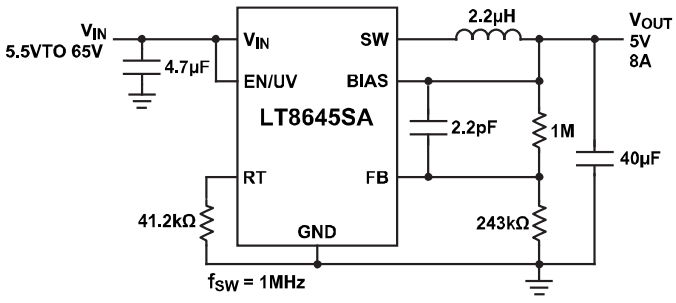

Figure 1. 5V 8A Step-Down Converter

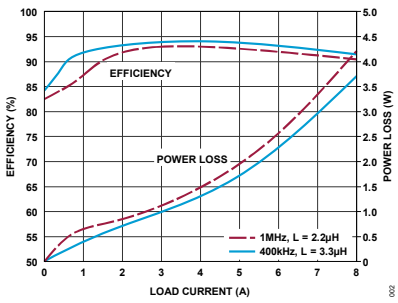

Figure 2. $24V_{IN}$ to $5V_{OUT}$ Efficiency

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REVISION HISTORY

REVISION	DATE	DESCRIPTION	PAGE NUMBER
0	10/25	Initial release	—

SPECIFICATIONS

Table 1. Electrical Characteristics

(Specifications are at T_J = -40°C to +125°C, unless otherwise noted. Typical values are at T_A = +25°C. All voltages are referenced to GND, unless otherwise noted. Specifications apply over the full operating temperature range, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Minimum Input Voltage	V_{IN}			3.0	3.4	V
V_{IN} Quiescent Current in Shutdown	$I_{Q(SHDN)}$	V_{IN} = 12V, $V_{EN/UV}$ = 0V, T_A = 25°C		0.9	3	µA
		V_{IN} = 12V, $V_{EN/UV}$ = 0V		0.9	10	µA
LT8645SA V_{IN} Quiescent Current in Sleep (Internal Compensation)	I_Q	V_{IN} = 6V, $V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V, T_A = 25°C		1.7	4	µA
		V_{IN} = 6V, $V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V		1.7	10	µA
LT8646SA V_{IN} Quiescent Current in Sleep (External Compensation)	I_Q	V_{IN} = 6V, $V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V, V_{BIAS} = 0V, T_A = 25°C		230	290	µA
		V_{IN} = 6V, $V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V, V_{BIAS} = 0V		230	340	µA
		V_{IN} = 6V, $V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V, V_{BIAS} = 5V, T_A = 25°C	16		25	µA
LT8646SA BIAS Quiescent Current in Sleep	$I_{Q(BIAS)}$	$V_{EN/UV}$ = 2V, V_{FB} > 0.97V, V_{SYNC} = 0V, V_{BIAS} = 5V, T_A = 25°C		200	260	µA
LT8645SA V_{IN} Current in Regulation	I_{IN}	V_{OUT} = 0.97V, V_{IN} = 6V, I_{LOAD} = 1mA, V_{SYNC} = 0V		250	500	µA
Feedback Reference Voltage	V_{FB}	V_{IN} = 6V , T_A = 25°C	0.964	0.970	0.976	V
		V_{IN} = 6V	0.958	0.970	0.978	V
Feedback Voltage Line Regulation	$\Delta V_{FB(LINE)}$	V_{IN} = 4.0V to 42V		0.004	0.02	%/V
Feedback Pin Input Current	I_{FB}	V_{FB} = 1V, T_A = 25°C	–20		20	nA
LT8646SA Error Amp Transconductance	$g_{m(EA)}$	V_C = 1.25V		1.7		mS
LT8646SA Error Amp Gain	A_V			400		V/V
LT8646SA V_C Source Current	I_{VC}	V_{FB} = 0.77V, V_C = 1.25V		350		µA
LT8646SA V_C Sink Current	I_{VC}	V_{FB} = 1.17V, V_C = 1.25V		350		µA
LT8646SA V_C Pin to Switch Current Gain	G_M			7		A/V

(Specifications are at T_J = -40°C to +125°C, unless otherwise noted. Typical values are at T_A = +25°C. All voltages are referenced to GND, unless otherwise noted. Specifications apply over the full operating temperature range, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
LT8646S V_C Clamp Voltage	V_{C_MAX}			2.6		V
BIAS Pin Current Consumption	I_{BIAS}	V_{BIAS} = 3.3V, f_{SW} = 2MHz		22		mA
Minimum On-Time	$t_{ON(MIN)}$	I_{LOAD} = 2A, FCM		35	55	ns
Minimum Off-Time	$t_{OFF(MIN)}$			80	110	ns
Oscillator Frequency	f_{SW}	R_T = 221k	180	210	240	kHz
		R_T = 60.4k	665	700	735	kHz
		R_T = 18.2k	1.8	1.95	2.1	MHz
Top Power NMOS On-Resistance	R_{TOP}	I_{SW} = 1A		40		mΩ
Top Power NMOS Current Limit	$I_{PEAK-LIMIT}$		10.5	14	17	A
Bottom Power NMOS On-Resistance	R_{BOT}	V_{INTVCC} = 3.4V, I_{SW} = 1A		25		mΩ
Bottom Power NMOS Current Limit	$I_{VALLEY-LIMIT}$	V_{INTVCC} = 3.4V, T_A = 25°C	9	12	15	A
SW Leakage Current	I_{SW-LKG}	V_{IN} = 65V, V_{SW} = 0V, 65V, T_A = 25°C	–3		3	µA
EN/UV Pin Threshold	V_{EN}	EN/UV Rising	0.95	1.01	1.07	V
EN/UV Pin Hysteresis	V_{EN-HYS}			45		mV
EN/UV Pin Current	I_{EN}	$V_{EN/UV}$ = 2V, T_A = 25°C	–20		20	nA
PG Upper Threshold Offset from V_{FB}	PGH	V_{FB} Falling	5	7.5	10	%
PG Lower Threshold Offset from V_{FB}	PGL	V_{FB} Rising	–10.5	–8	–5.5	%
PG Hysteresis	PG_{HYS}	T_A = 25°C		0.4		%
PG Leakage	I_{PG-LKG}	V_{PG} = 3.3V, T_A = 25°C	–40		40	nA
PG Pull-Down Resistance	R_{PG}	V_{PG} = 0.1V		700	2000	Ω
SYNC/MODE Threshold	$V_{SYNC/MODE}$	SYNC/MODE DC and Clock Low Level Voltage	0.7			V
		SYNC/MODE Clock High Level Voltage			1.4	V
		SYNC/MODE DC High Level Voltage	2.2		2.9	V
Spread Spectrum Modulation Frequency Range	Δf_{SSFM}	R_T = 60.4k, V_{SYNC} = 3.3V		24		%

(Specifications are at T_J = -40°C to +125°C, unless otherwise noted. Typical values are at T_A = +25°C. All voltages are referenced to GND, unless otherwise noted. Specifications apply over the full operating temperature range, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Spread Spectrum Modulation Frequency	f_{SSFM}	V_{SYNC} = 3.3V		2.5		kHz
TR/SS Source Current	I_{SS}		1.3	2	2.7	µA
TR/SS Pull-Down Resistance	R_{SS}	Fault Condition, TR/SS = 0.1V		200		Ω
V_{IN} to Disable Forced Continuous Mode	$V_{IN-OV-FCM}$	V_{IN} Rising, T_A = 25°C	60	63.5		V

1 The LT8645SA/LT8646SA is specified over the –40°C to 125°C operating junction temperature range. High junction temperatures degrade operating lifetimes. The junction temperature (T_J in °C) is calculated from the ambient temperature (T_A in °C) and power dissipation (PD, in Watts) according to the formula:

$T_J = T_A + (PD \bullet \theta_{JA})$

where θ_{JA} (in °C/W) is the package thermal impedance.

2 θ values determined per JEDEC 51-7, 51-12. See the *Applications Information* section for information on improving the thermal resistance and for actual temperature measurements of a demo board in typical operating conditions.

3 This IC includes overtemperature protection that is intended to protect the device during overload conditions. Junction temperature will exceed 150°C when overtemperature protection is active. Continuous operation above the specified maximum operating junction temperature will reduce lifetime.

ABSOLUTE MAXIMUM RATINGS

T_A = 25°C, unless otherwise specified.

Table 2. Absolute Maximum Ratings

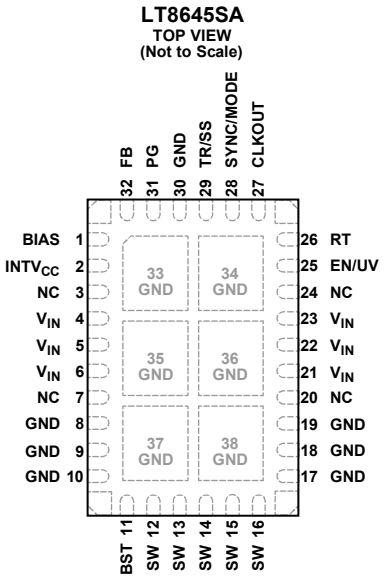
PARAMETER	RATING
V_{IN}, EN/UV	70V
PG	42V
BIAS	25V
FB, TR/SS	4V
SYNC/MODE Voltage	6V
Operating Junction Temperature Range (Note 2)	–40°C to 125°C
Storage Temperature Range	–65°C to 150°C
Maximum Reflow (Package Body) Temperature	260°C

Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. These are stress ratings only, functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

Thermal Resistance

Thermal performance is directly linked to PCB design and operating environment. Close attention to PCB thermal design is required.

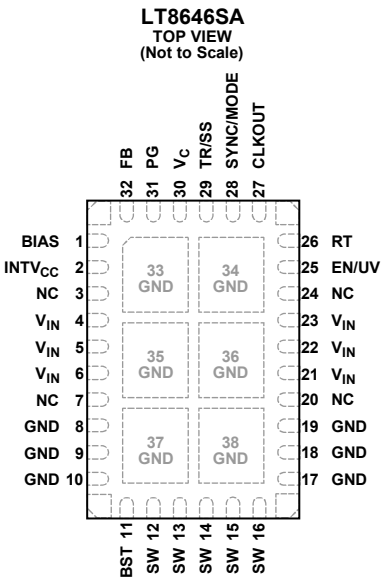
PIN CONFIGURATIONS AND FUNCTION DESCRIPTIONS



NOTES
1. EXPOSED PADS (PINS 33-38) ARE GND, SHOULD BE SOLDERED TO PCB
2. NC = NO CONNECT.

LQFN PACKAGE
32-LEAD (6mm × 4mm × 0.94mm)
EVAL BOARD: θ_{JA} = 18°C/W, Ψ_{JT} = 0.5°C/W,
θ_{JCTOP} = 31.9°C/W, $\theta_{JC(PAD)}$ = 4.6°C/W (NOTE 2)

003



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004

Table 3. Pin Descriptions

PIN	NAME	DESCRIPTION
1	BIAS	The internal regulator will draw current from BIAS instead of V_{IN} when BIAS is tied to a voltage higher than 3.1V. For output voltages of 3.3V to 25V this pin should be tied to V_{OUT}. If this pin is tied to a supply other than V_{OUT} use a 1µF local bypass capacitor on this pin. If no supply is available, tie to GND. However, especially for high input or high frequency applications, BIAS should be tied to output or an external supply of 3.3V or above.
2	$INTV_{CC}$	Internal 3.4V Regulator Bypass Pin. The internal power drivers and control circuits are powered from this voltage. $INTV_{CC}$ maximum output current is 25mA. Do not load the $INTV_{CC}$ pin with external circuitry. $INTV_{CC}$ current will be supplied from BIAS if BIAS > 3.1V, otherwise current will be drawn from V_{IN}. Voltage on $INTV_{CC}$ will vary between 2.8V and 3.4V when BIAS is between 3.0V and 3.6V. This pin should be floated.
3, 7, 20, 24	NC	No Connect. This pin is not connected to internal circuitry and can be tied anywhere on the PCB, typically ground.
4-6, 21-23	V_{IN}	The V_{IN} pins supply current to the LT8645SA/LT8646SA internal circuitry and to the internal topside power switch. These pins must be tied together and be locally bypassed with a capacitor of 4.7µF or more. Be sure to place the positive terminal of the input capacitor as close as possible to the V_{IN} pins, and the negative capacitor

		terminal as close as possible to the GND pins. See the *Applications Information* section for a sample layout.
8-10, 17-19, 33–38	GND	Ground. Place the negative terminal of the input capacitor as close to the GND pins as possible. See the *Applications Information* section for a sample layout. The exposed pads should be soldered to the PCB for good thermal performance. If necessary due to manufacturing limitations pins 33 to 38 may be left disconnected. However, thermal performance will be degraded.
11	BST	This pin is used to provide a drive voltage, higher than the input voltage, to the topside power switch. This pin should be floated.
12-16	SW	The SW pins are the outputs of the internal power switches. Tie these pins together and connect them to the inductor and boost capacitor. This node should be kept small on the PCB for good performance and low EM.
25	EN/UV	The LT8645SA/LT8646SA shuts down when this pin is low and active when this pin is high. The hysteretic threshold voltage is 1.01V going up and 0.965V going down. Tie to V_{IN} if the shutdown feature is not used. An external resistor divider from V_{IN} can be used to program a V_{IN} threshold below which the LT8645SA/LT8646SA will shut down.
26	RT	A resistor is tied between RT and ground to set the switching frequency.
27	CLKOUT	In Forced Continuous Mode (FCM) mode, spread spectrum, and synchronization modes, the CLKOUT pin provides a 50% duty cycle square wave 180° out of phase with the switching frequency. The low and high levels of the CLKOUT pin are ground and $INTV_{CC}$, respectively. In Burst Mode operation, the CLKOUT pin will be low. Float this pin if the CLKOUT function is not used.
28	SYNC/MODE	This pin programs four different operating modes: 1) Burst Mode: Tie this pin to ground for Burst Mode operation at low output loads—this will result in ultralow quiescent current. 2) Forced Continuous Mode (FCM): This mode offers fast response and full frequency operation over a wide load range. Float this pin for FCM. When floating, pin leakage currents should be <1µA. 3) Spread Spectrum Mode: Tie this pin high to $INTV_{CC}$ (or >3V) for Forced Continuous Mode (FCM) with spread spectrum modulation. 4) Synchronization Mode: Drive this pin with a clock source to synchronize to an external frequency. During synchronization, the part operates in Forced Continuous Mode (FCM).
29	TR/SS	Output Tracking and Soft-Start Pin. This pin allows user control of output voltage ramp rate during start-up. For the LT8645SA, a TR/SS voltage below 0.97V forces it to regulate the FB pin to equal the TR/SS pin voltage. When TR/SS is above 0.97V, the tracking function is disabled and the internal reference resumes control of the error amplifier. For the LT8646SA, a TR/SS voltage below 1.6V forces it to regulate the FB pin to a function of the TR/SS pin voltage. See plot in the *Typical Performance Characteristics* section. When TR/SS is above 1.6V, the tracking function is disabled and the internal reference resumes control of the error amplifier. An internal 2µA pull-up current from $INTV_{CC}$ on this pin allows a capacitor to program output voltage slew rate. This pin is pulled to ground with an internal 200Ω MOSFET during shutdown and fault conditions; use a series resistor if driving from a low impedance output. This pin may be left floating if the tracking function is not needed.

30, LT8645SA Only	GND	Ground. Connect this pin to system ground and to the ground plane. This pin is also connected to ground internally, and can be left floating on PCB to be pin compatible with the LT8646SA.
30, LT8646SA Only	V_C	The V_C pin is the output of the internal error amplifier. The voltage on this pin controls the peak switch current. Tie an RC network from this pin to ground to compensate the control loop.
31	PG	The PG pin is the open-drain output of an internal comparator. PG remains low until the FB pin is within ±8% of the final regulation voltage, and there are no fault conditions. PG is pulled low when EN/UV is below 1V, $INTV_{CC}$ has fallen too low, V_{IN} is too low, or thermal shutdown. PG is valid when V_{IN} is above 3.4V.
32	FB	The LT8645SA/LT8646SA regulates the FB pin to 0.97V. Connect the feedback resistor divider tap to this pin. Also, connect a phase lead capacitor between FB and V_{OUT}. Typically, this capacitor is 1pF to 10pF.
	Corner Pins	These pins are for mechanical support only and can be tied anywhere on the PCB, typically ground.

TYPICAL PERFORMANCE CHARACTERISTICS

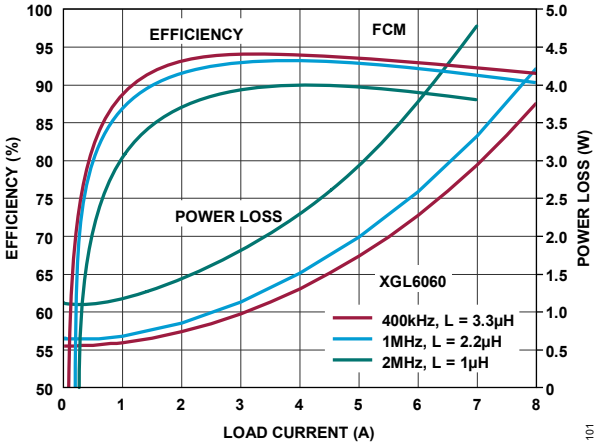


Figure 3. 24V_{IN} to 5V_{OUT} Efficiency vs Frequency

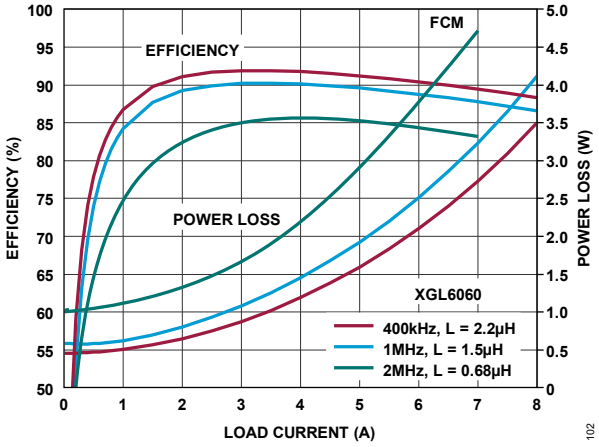


Figure 4. 24V_{IN} to 3.3V_{OUT} Efficiency vs Frequency

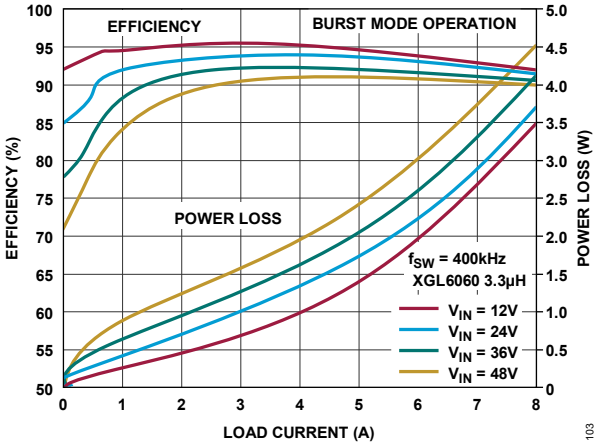


Figure 5. Efficiency at 5V_{OUT}

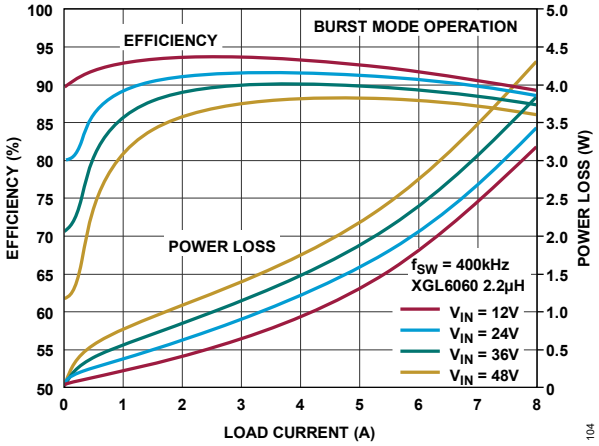


Figure 6. Efficiency at 3.3V_{OUT}

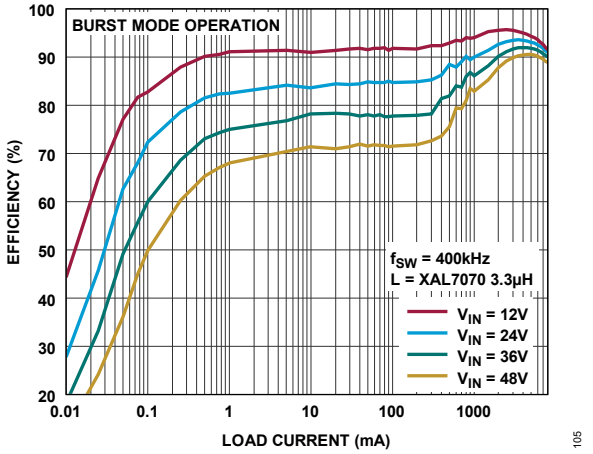


Figure 7. LT8645SA Low Load Efficiency at 5V_{OUT}

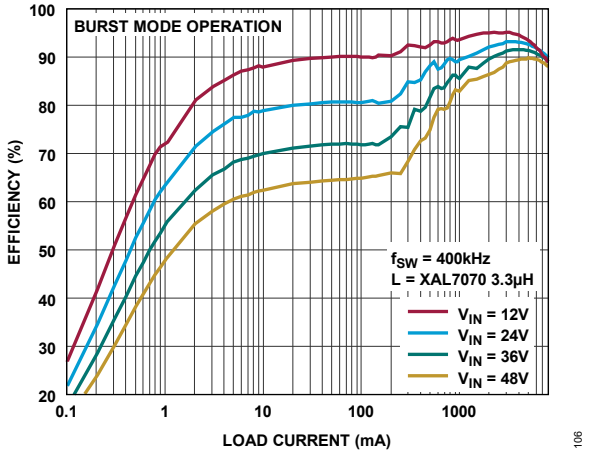


Figure 8. LT8646SA Low Load Efficiency at 5V_{OUT}

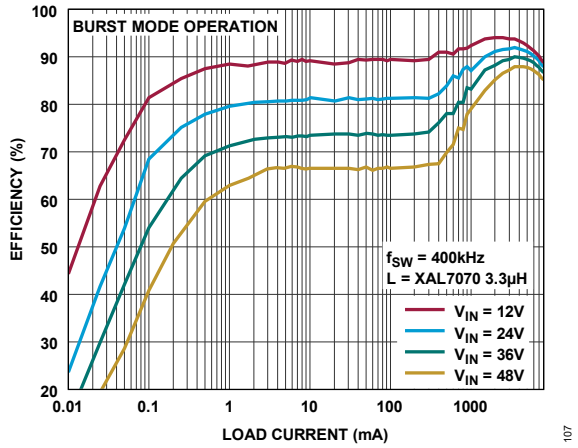


Figure 9. LT8645SA Low Load Efficiency at 3.3V_{OUT}

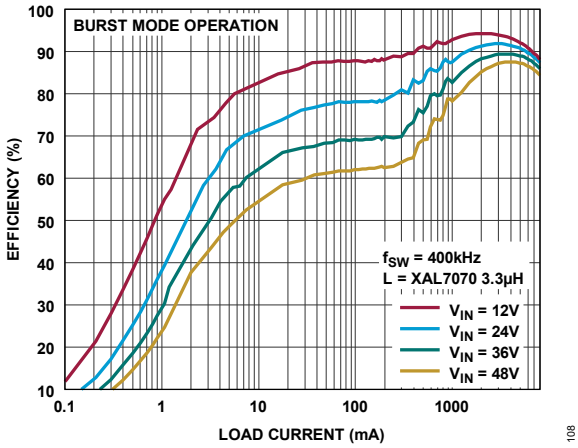


Figure 10. LT8646SA Low Load Efficiency at 3.3V_{OUT}

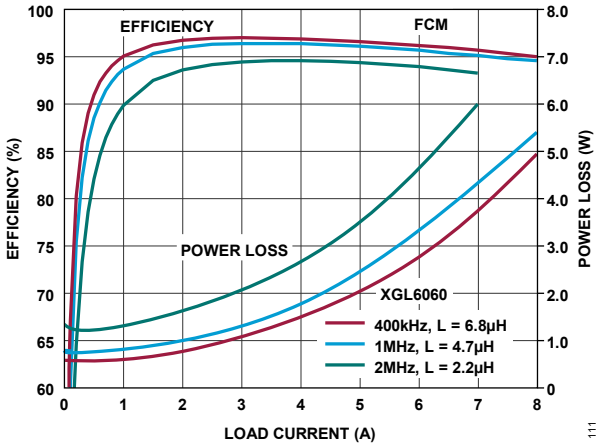


Figure 11. 24V_{IN} to 12V_{OUT} Efficiency vs Frequency

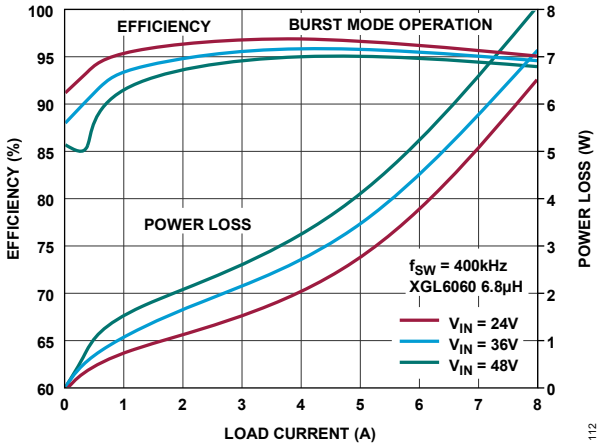


Figure 12. 12V_{OUT} Efficiency

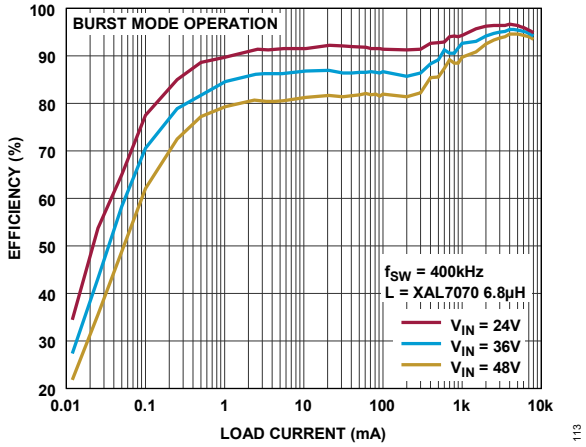


Figure 13. LT8645SA Low Load Efficiency at 12V_{OUT}

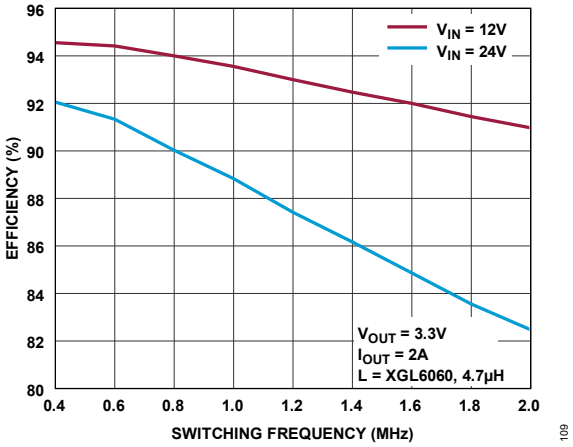


Figure 14. Efficiency vs Frequency

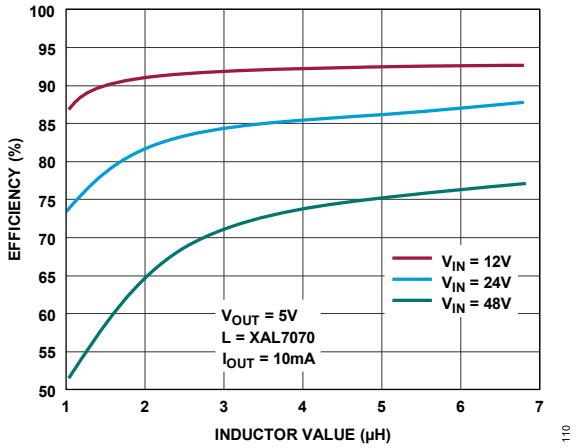


Figure 15. Burst Mode Operation Efficiency vs Inductor Value (LT8645SA)

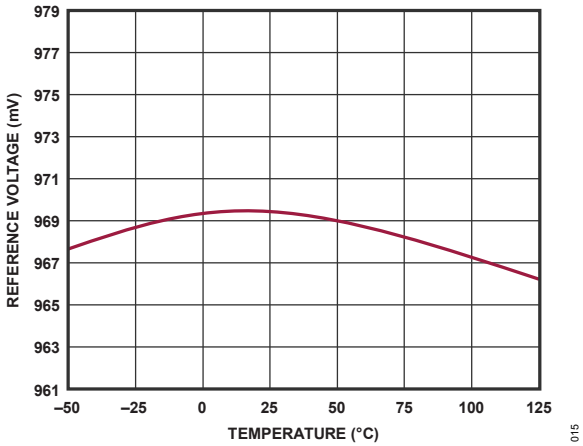


Figure 16. Reference Voltage

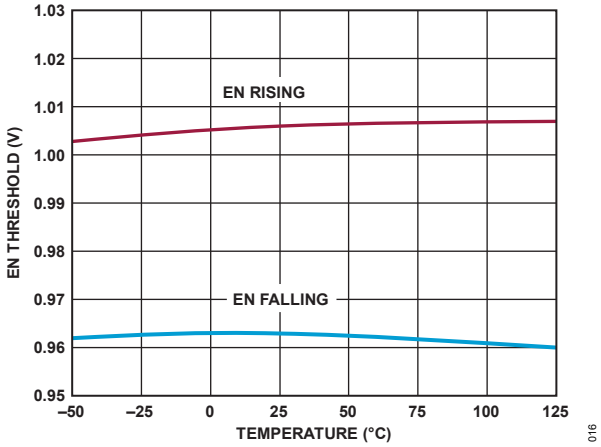


Figure 17. EN Pin Thresholds

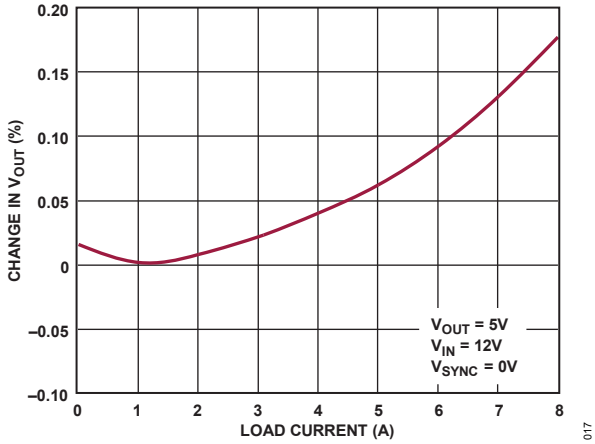


Figure 18. LT8645SA Load Regulation

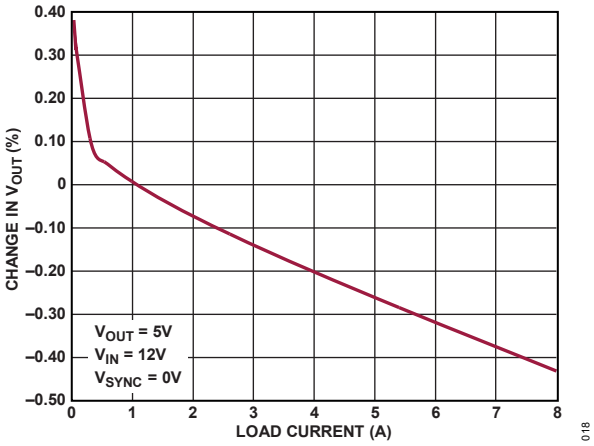


Figure 19. LT8646SA Load Regulation

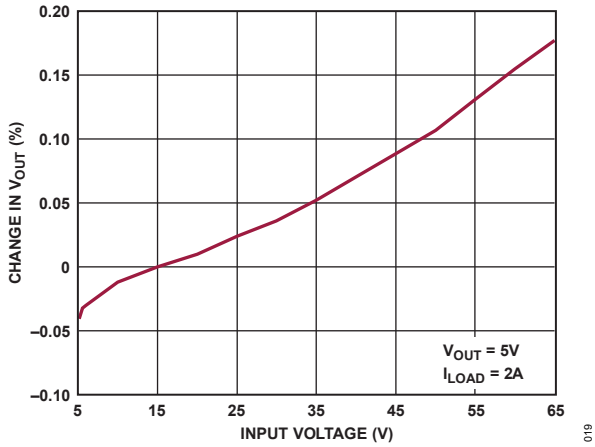


Figure 20. LT8645SA Line Regulation

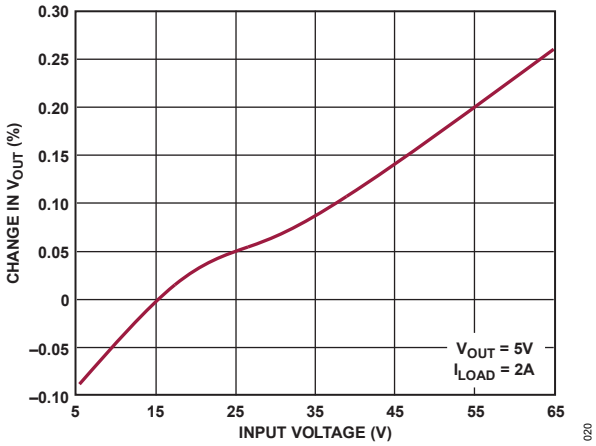


Figure 21. LT8646SA Line Regulation

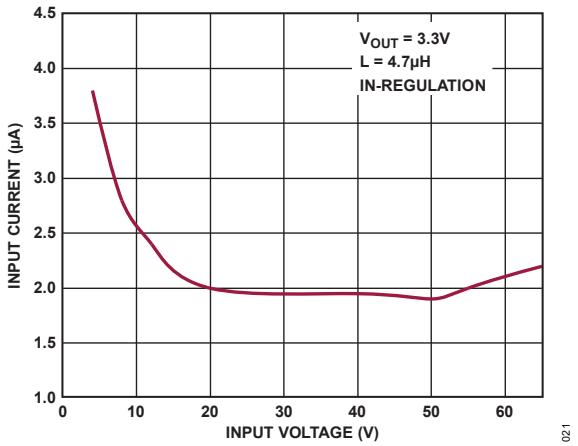


Figure 22. LT8645SA No-Load Supply Current

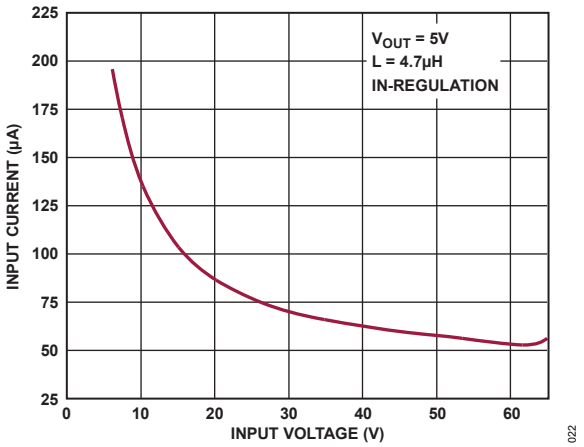


Figure 23. LT8646SA No-Load Supply Current

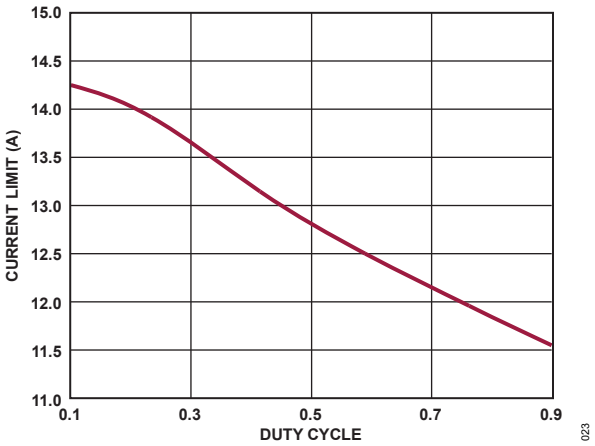


Figure 24. Top FET Current Limit vs Duty Cycle

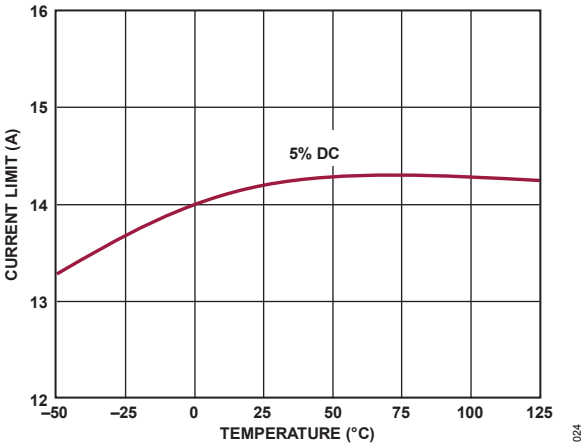


Figure 25. Top FET Current Limit

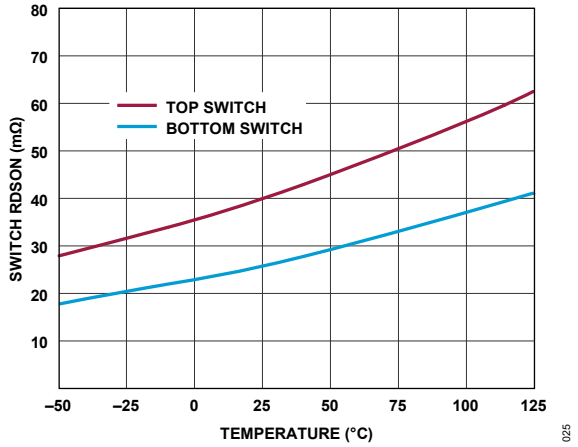


Figure 26. Switch RDSON vs Temperature

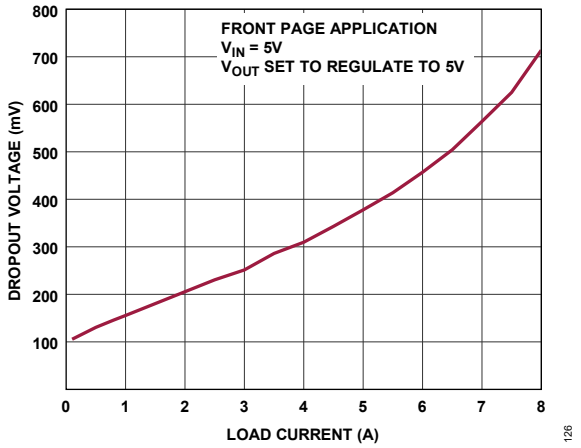


Figure 27. Dropout voltage

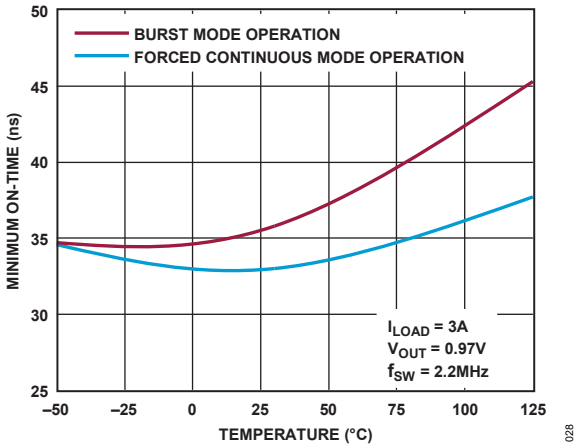


Figure 28. Minimum On-Time

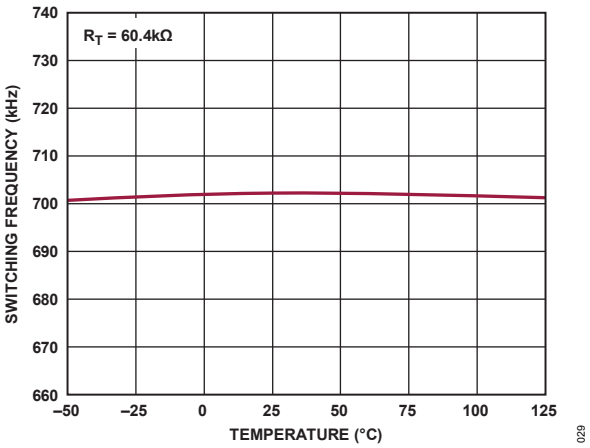


Figure 29. Switching Frequency

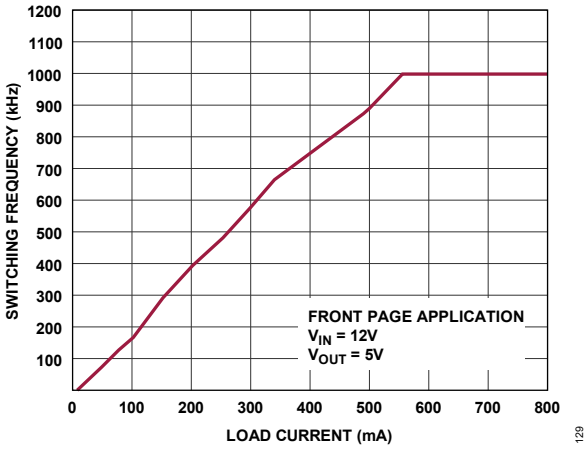


Figure 30. Burst Frequency

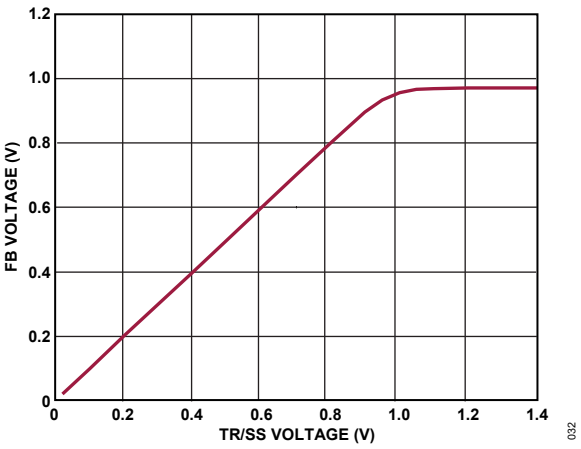


Figure 31. LT8645SA Soft-Start Tracking

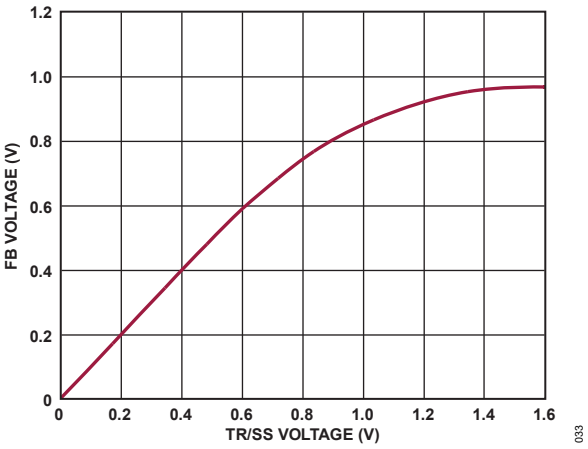


Figure 32. LT8646SA Soft-Start Tracking

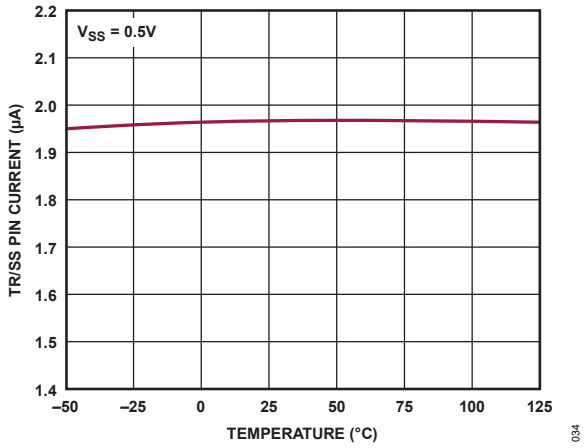


Figure 33. Soft-Start Current

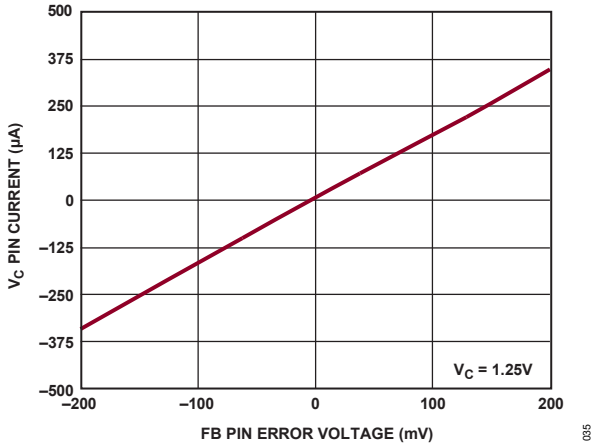


Figure 34. LT8646SA Error Amp Output Current

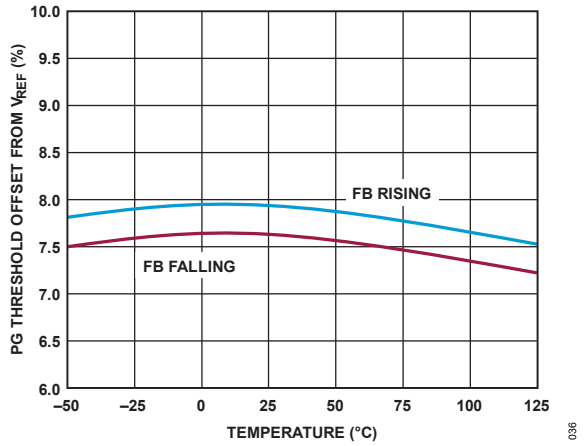


Figure 35. PG High Thresholds

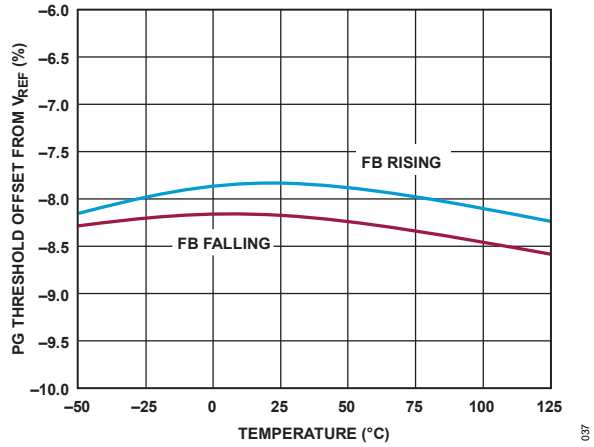


Figure 36. PG Low Thresholds

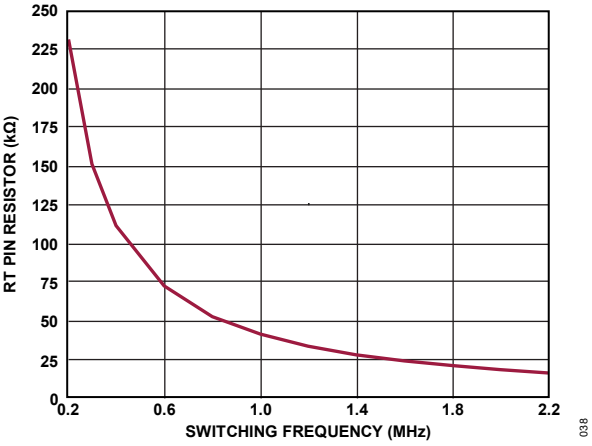


Figure 37. RT Programmed Switching Frequency

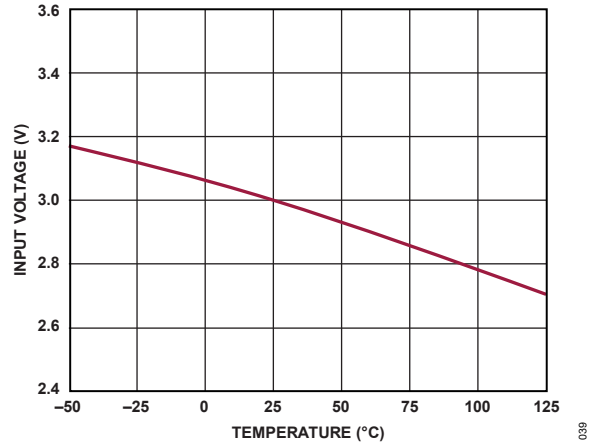


Figure 38. Minimum Input Voltage

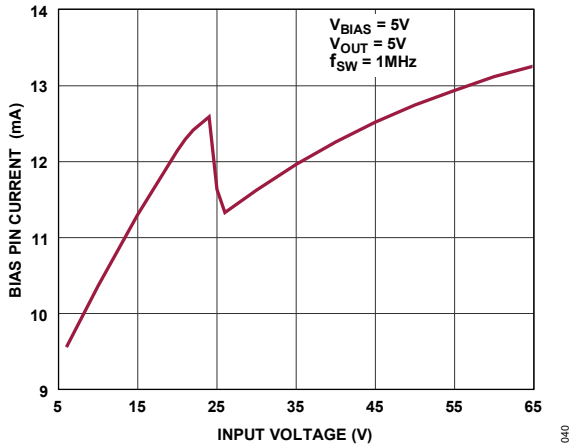


Figure 39. Bias Pin Current

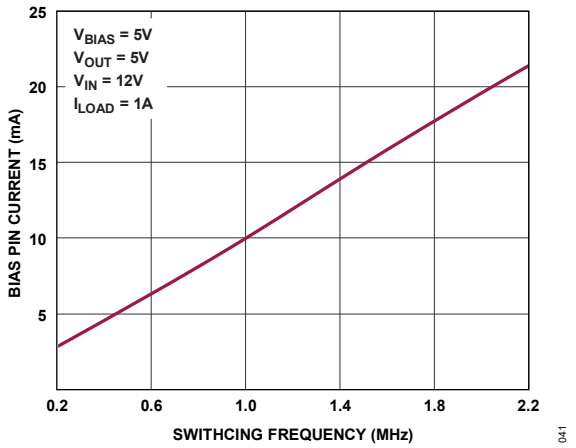


Figure 40. Bias Pin Current

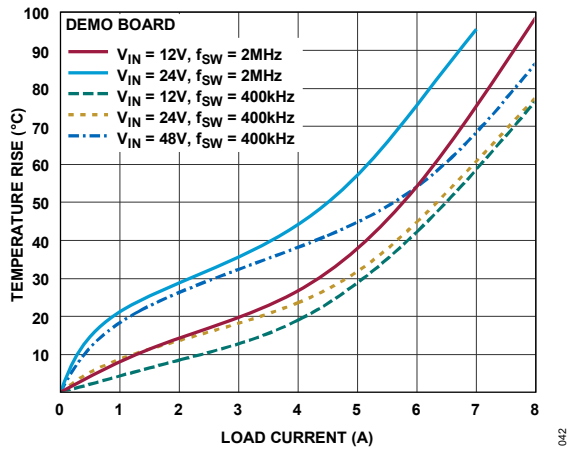


Figure 41. Case Temperature Rise

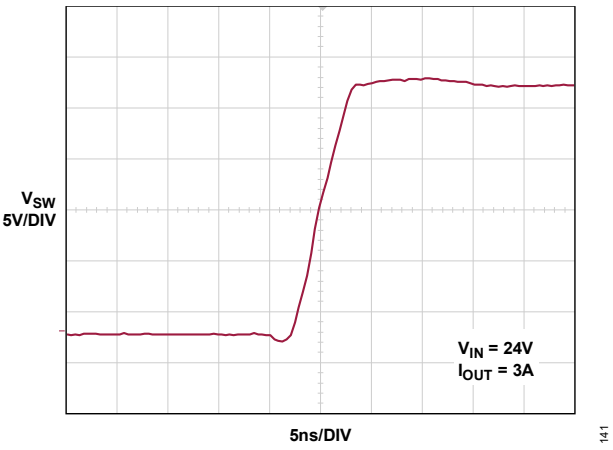


Figure 42. Switch Rising Edge

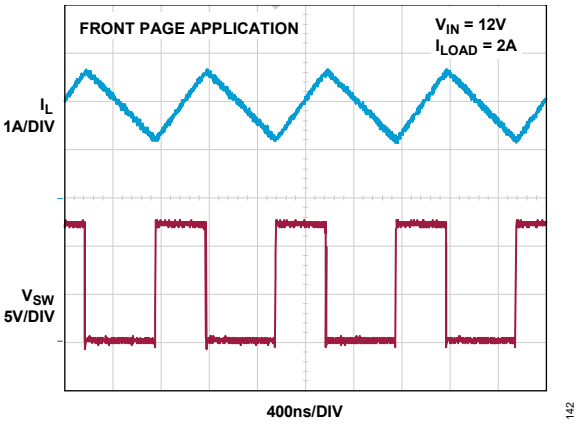


Figure 43. Switching Waveforms, Full Frequency Continuous Operation

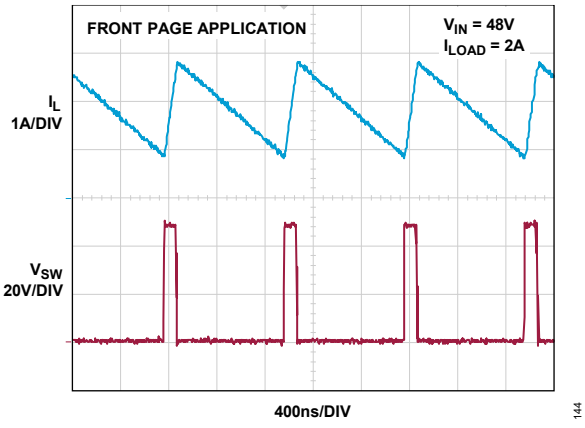


Figure 44. Switching Waveforms, Full Frequency Continuous Operation

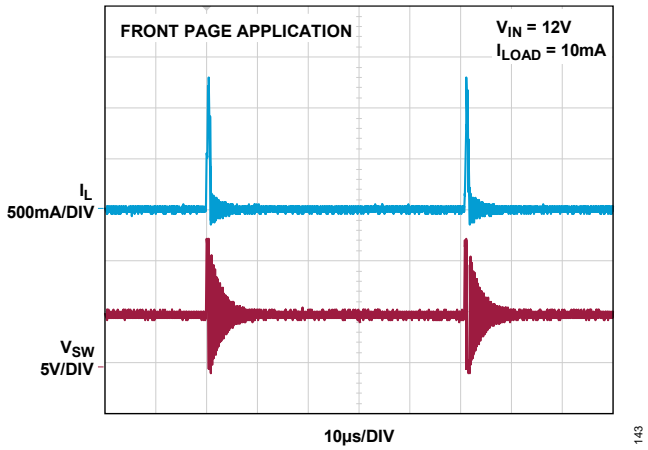


Figure 45. Switching Waveforms, Burst Mode Operation

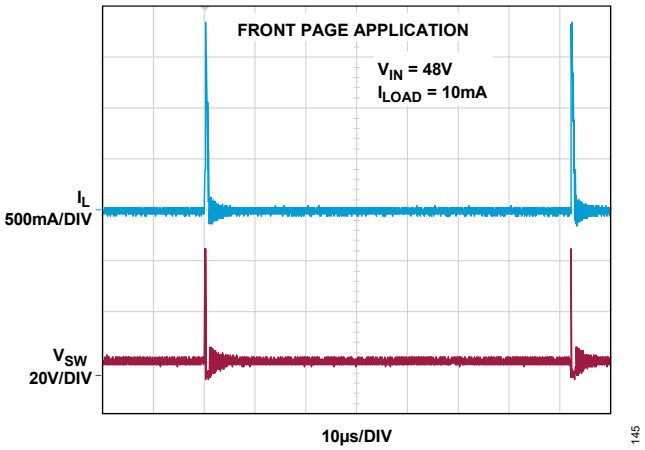


Figure 46. Switching Waveforms, Burst Mode Operation

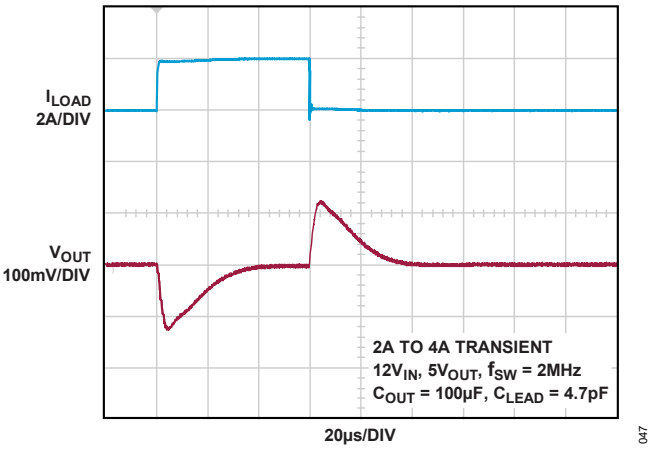


Figure 47. LT8645SA Transient Response; Internal Compensation

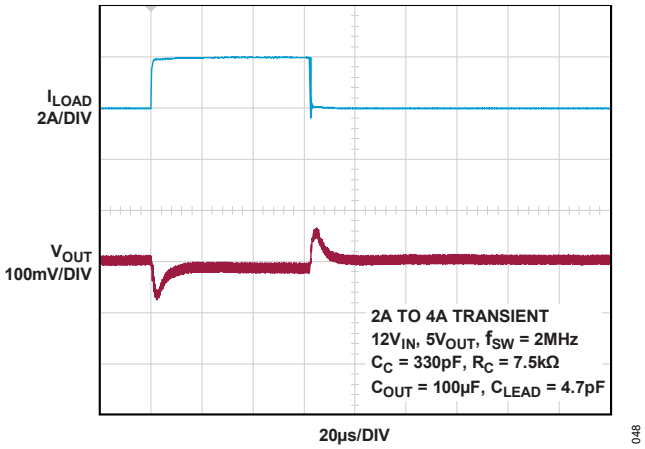


Figure 48. LT8646SA Transient Response; External Compensation

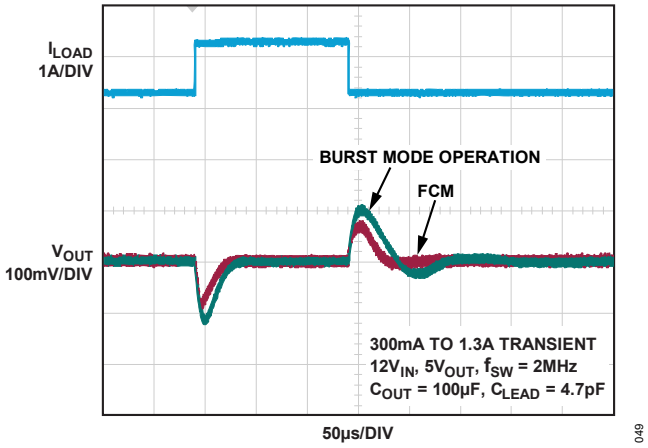


Figure 49. LT8645SA Transient Response; 300mA to 1.3A Load Step

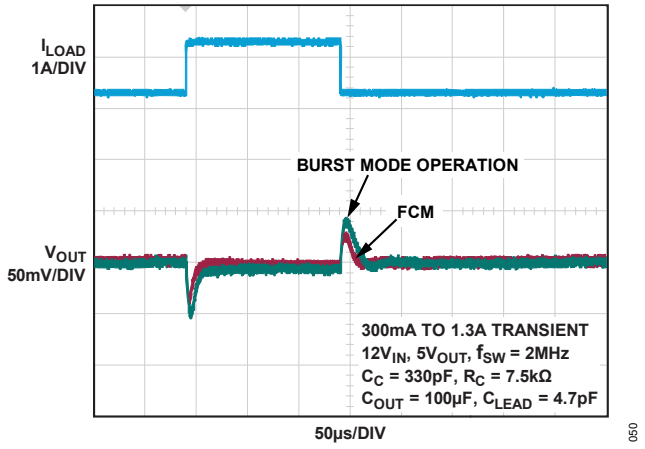


Figure 50. LT8646SA Transient Response; 300mA to 1.3A Load Step

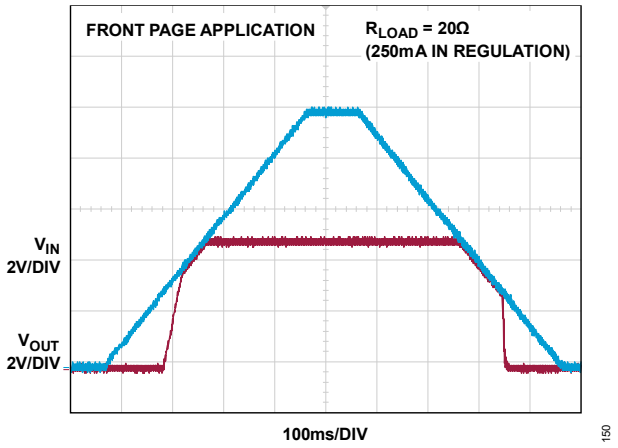


Figure 51. Start-Up Dropout Performance

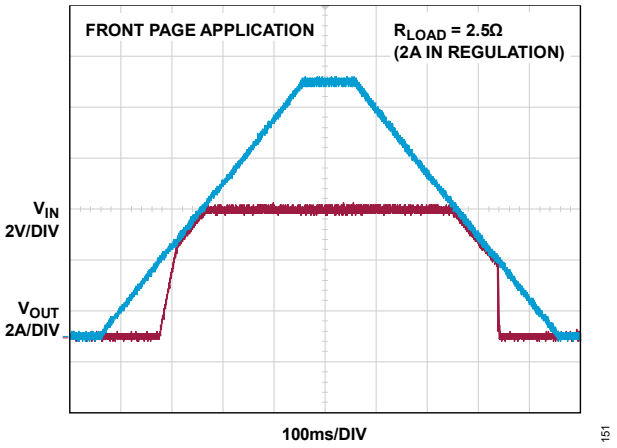


Figure 52. Start-Up Dropout Performance

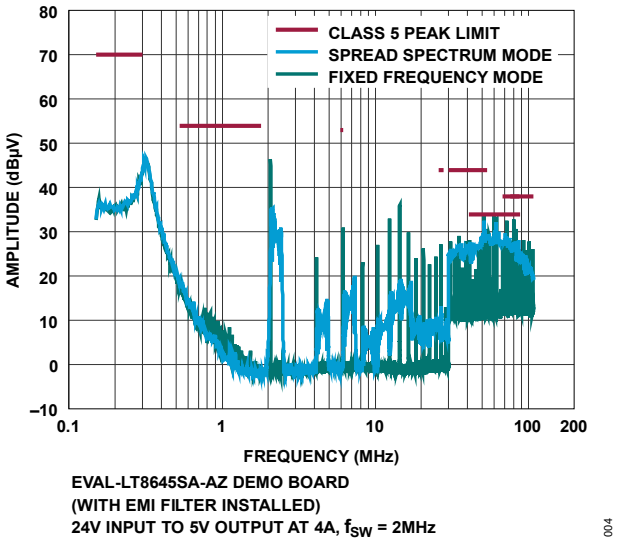


Figure 53. Conducted EMI Performance (CISPR25 Conducted Emission Test with Class 5 Peak Limits)

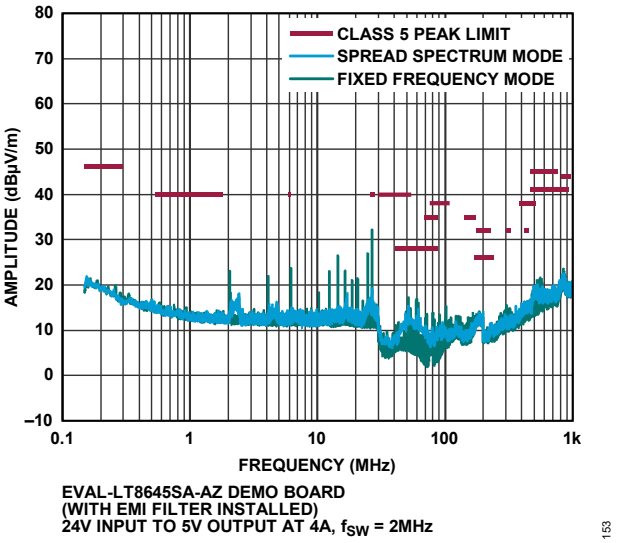


Figure 54. Radiated EMI Performance (CISPR25 Radiated Emission Test with Class 5 Peak Limits)

BLOCK DIAGRAM

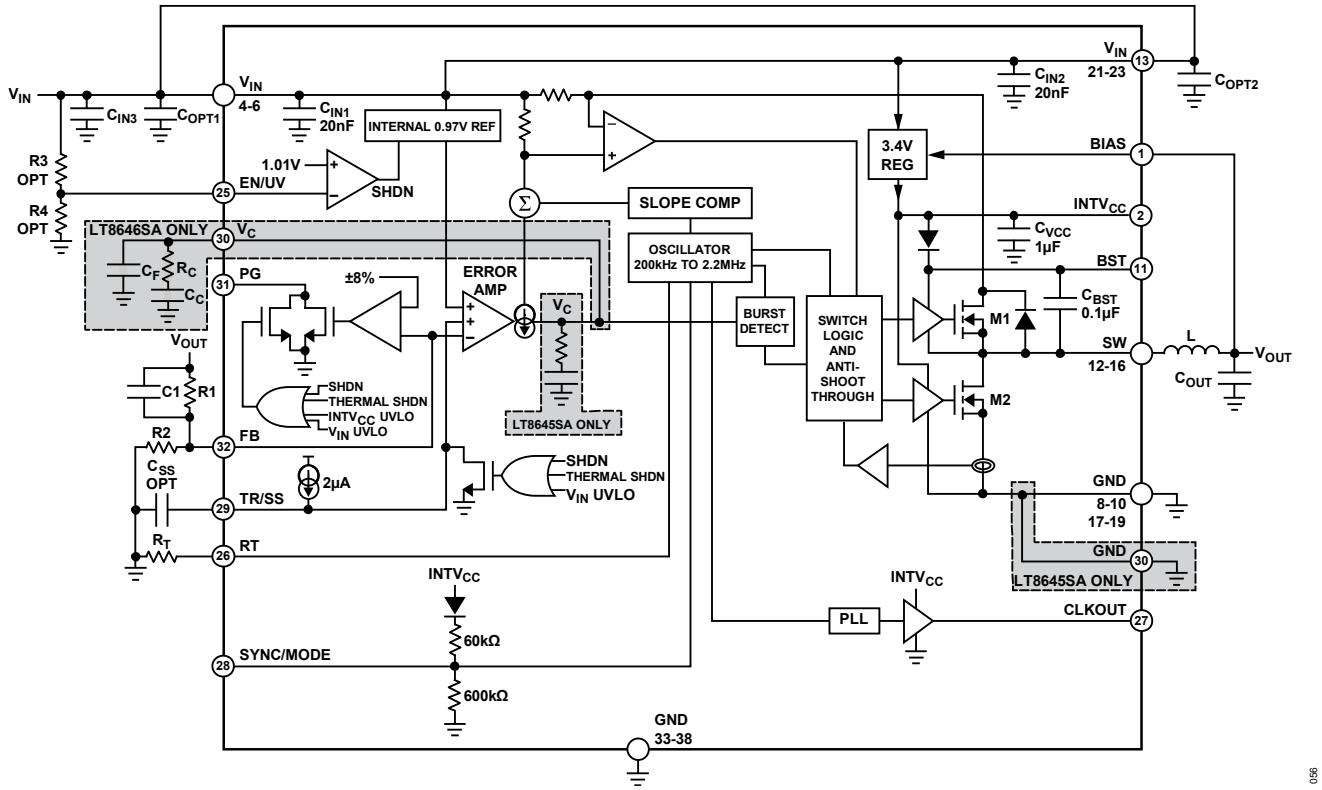


Figure 55. Block Diagram

THEORY OF OPERATION

The LT8645SA/LT8646SA is a monolithic, constant frequency, current mode step-down DC/DC converter. An oscillator, with frequency set using a resistor on the RT pin, turns on the internal top power switch at the beginning of each clock cycle. Current in the inductor then increases until the top switch current comparator trips and turns off the top power switch. The peak inductor current at which the top switch turns off is controlled by the voltage on the internal V_C node. The error amplifier servos the V_C node by comparing the voltage on the V_{FB} pin with an internal 0.97V reference. When the load current increases, it causes a reduction in the feedback voltage relative to the reference, leading the error amplifier to raise the V_C voltage until the average inductor current matches the new load current. When the top power switch turns off, the synchronous power switch turns on until the next clock cycle begins or inductor current falls to zero. If overload conditions result in more than 12A flowing through the bottom switch, the next clock cycle will be delayed until switch current returns to a safe level.

The S in LT8645SA/LT8646SA refers to the second-generation Silent Switcher technology. This technology allows fast switching edges for high efficiency at high switching frequencies, while simultaneously achieving good EMI performance. This includes the integration of ceramic capacitors into the package for V_{IN}, BST, and $INTV_{CC}$ (see *Block Diagram*). These caps keep all the fast AC current loops small, which improves EMI performance.

If the EN/UV pin is low, the LT8645SA/LT8646SA shuts down and draws approximately 1µA from the input. When the EN/UV pin is above 1.01V, the switching regulator becomes active.

To optimize efficiency at light loads, the LT8645SA/LT8646SA operates in Burst Mode operation in light load situations. Between bursts, all circuitry associated with controlling the output switch is shut down, reducing the input supply current to 1.7µA (LT8645SA) or 230µA (LT8646SA with BIAS = 0). In a typical application, 2.5µA (LT8645SA) or 120µA (LT8646SA with BIAS = $5V_{OUT}$) will be consumed from the input supply when regulating with no load. The SYNC/MODE pin is tied low to use Burst Mode operation and can be floated to use forced continuous mode (FCM). If a clock is applied to the SYNC/MODE pin, the part will synchronize to an external clock frequency and operate in FCM.

The LT8645SA/LT8646SA can operate in forced continuous mode (FCM) for fast transient response and full frequency operation over a wide load range. When in FCM, the oscillator operates continuously, and positive SW transitions are aligned to the clock. Negative inductor current is allowed. The LT8645SA/LT8646SA can sink current from the output and return this charge to the input in this mode, improving load step transient response.

To improve EMI, the LT8645SA/LT8646SA can operate in spread spectrum mode. This feature varies the clock with a triangular frequency modulation of +20%. For example, if the LT8645SA/LT8646SA's frequency is programmed to switch at 2MHz, spread spectrum mode will modulate the oscillator between 2MHz and 2.4MHz. The SYNC/MODE pin should be tied high to $INTV_{CC}$ (or >3V) to enable spread spectrum modulation with forced continuous mode.

To improve efficiency across all loads, supply current to internal circuitry can be sourced from the BIAS pin when biased at 3.3V or above. Else, the internal circuitry will draw current from V_{IN}. The BIAS pin should be connected to V_{OUT}, if the LT8645SA/LT8646SA output is programmed at 3.3V to 25V.

The V_C pin optimizes the loop compensation of the switching regulator based on the programmed switching frequency, allowing for a fast transient response. The V_C pin also enables current sharing and a CLKOUT pin enables synchronizing other regulators to the LT8646SA.

Comparators monitoring the FB pin voltage will pull the PG pin low if the output voltage varies more than ±8% (typical) from the set point, or if a fault condition is present.

APPLICATIONS INFORMATION

Low EMI PCB Layout

The LT8645SA/LT8646SA is specifically designed to minimize EMI emissions and also to maximize efficiency when switching at high frequencies. For optimal performance, the LT8645SA/LT8646SA should use multiple V_{IN} bypass capacitors.

Two small 0.47µF capacitors can be placed as close as possible to the LT8645SA/LT8646SA: One capacitor on each side of the device (C_{OPT1}, C_{OPT2}). A third capacitor with a larger value, 4.7µF or higher, should be placed near C_{OPT1} or C_{OPT2}.

See *Figure 56, Figure 57* for recommended PCB layouts.

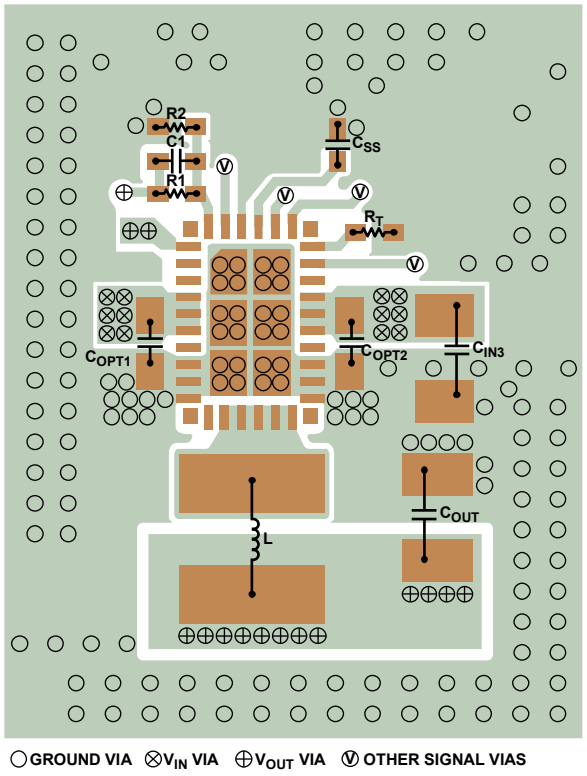


Figure 56. Recommended PCB Layout for the LT8645SA

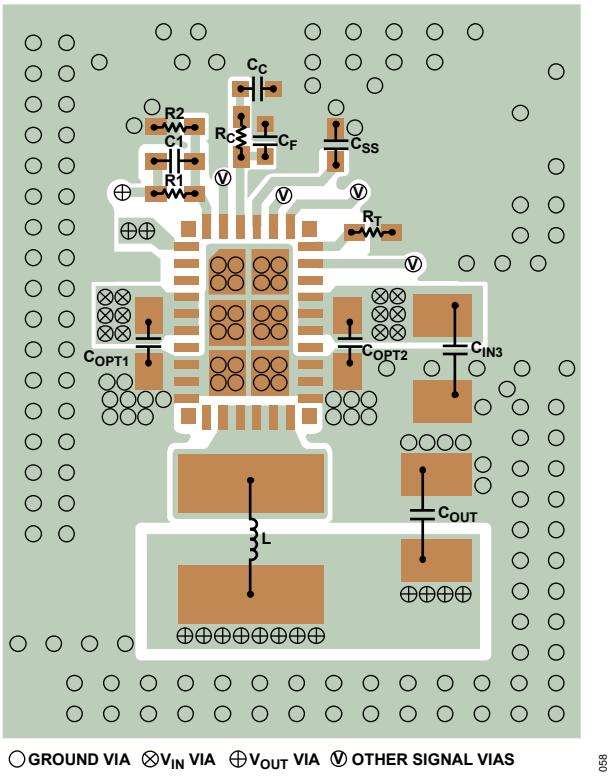


Figure 57. Recommended PCB Layout for the LT8646SA

For more detail and PCB design files refer to the EVAL BOARD-LT8645SA user guides for the LT8645SA/LT8646SA.

Note that large, switched currents flow in the LT8645SA/LT8646SA V_{IN} and GND pins and the input capacitors. The loops formed by the input capacitors should be as small as possible by placing the capacitors adjacent to the V_{IN} and GND pins. Capacitors with small case size such as 0603 or 0805 are optimal due to lowest parasitic inductance.

The input capacitors, along with the inductor and output capacitors, should be placed on the same side of the circuit board, and their connections should be made on that layer. Place a local, unbroken ground plane under the application circuit on the layer closest to the surface layer. The SW and BOOST nodes should be as small as possible. Finally, keep the FB and RT nodes small so that the ground traces will shield them from the SW and BOOST nodes.

The exposed pads on the bottom of the package should be soldered to the PCB to reduce thermal resistance to ambient. To keep thermal resistance low, extend the ground plane from the GND pins as much as possible, and add thermal vias to additional ground planes within the circuit board and on the bottom side.

Burst Mode Operation

To enhance efficiency at light loads, the LT8645SA/LT8646SA operates in low ripple Burst Mode operation, which keeps the output capacitor charged to the desired output voltage while minimizing the input quiescent current and minimizing output voltage ripple. In Burst Mode operation, the LT8645SA/LT8646SA delivers single small pulses of current to the output capacitor followed by sleep periods where the output power is supplied by the output capacitor. While in sleep mode the LT8645SA consumes 1.7µA, and the LT8646SA consumes 230µA.

As the output load decreases, the frequency of single current pulses decreases (see *Figure 59*) and the percentage of time the LT8645SA/LT8646SA is in sleep mode increases, resulting in much higher light load efficiency than for typical converters. By maximizing the time between pulses, the LT8645SA's quiescent current approaches 2.5µA for a typical application when there is no output load. Therefore, to optimize the quiescent current performance at light loads, the current in the feedback resistor divider must be minimized as it appears to the output as load current.

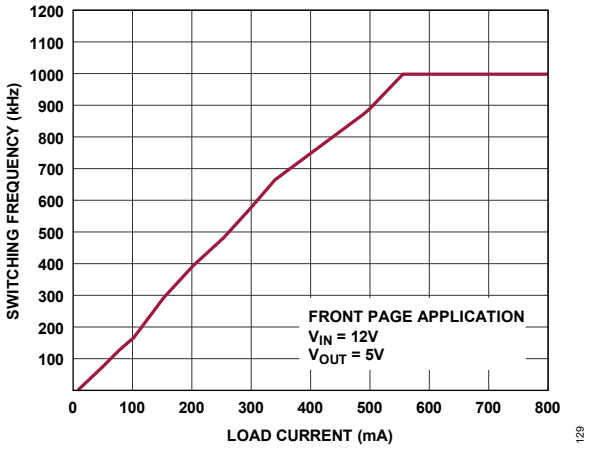


Figure 58. SW Frequency vs Load Information in Burst Mode Operation

In order to achieve higher light load efficiency, more energy must be delivered to the output during the single small pulses in Burst Mode operation such that the LT8645SA/LT8646SA can stay in sleep mode longer between each pulse. This can be achieved by using a larger value inductor (i.e., 4.7µH), and should be considered independent of switching frequency when choosing an inductor. For example, while a lower inductor value would typically be used for a high switching frequency application, if high light load efficiency is desired, a higher inductor value should be chosen. See the curve in *Typical Performance Characteristics*.

While in Burst Mode operation, the current limit of the top switch is approximately 1.25A (as shown in *Figure 59*), resulting in low output voltage ripple. Increasing the output capacitance will decrease output ripple proportionally. As the load ramps upward from zero, the switching frequency will increase but only up to the switching frequency programmed by the resistor at the RT pin, as shown in *Figure 58*.

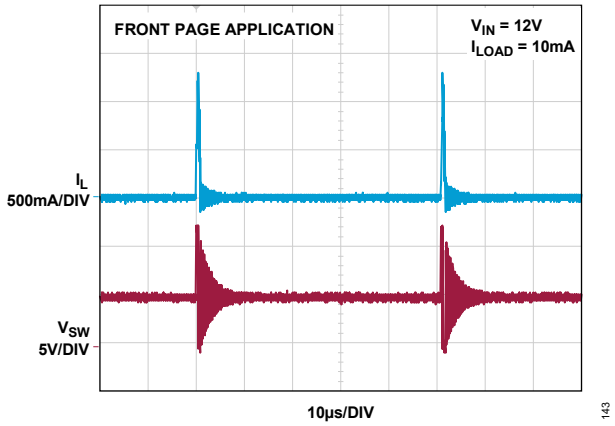


Figure 59. Burst Mode Operation

The output load at which the LT8645SA/LT8646SA reaches the programmed frequency varies based on input voltage, output voltage, and inductor choice. To select low ripple Burst Mode operation, tie the SYNC/MODE pin below 0.4V (this can be ground or a logic low output).

Forced Continuous Mode (FCM)

The LT8645SA/LT8646SA can operate in forced continuous mode (FCM) for fast transient response and full frequency operation over a wide load range. When in FCM, the oscillator operates continuously, and positive SW transitions are aligned to the clock. Negative inductor current is allowed at light loads or under large transient conditions. The LT8645SA/LT8646SA can sink current from the output and return this charge to the input in this mode, improving load step transient response. At light loads, FCM operation is less efficient than Burst Mode operation, but may be desirable in applications where it is necessary to keep switching harmonics out of the signal band. FCM must be used if the output is required to sink current. To enable FCM, float the SYNC/MODE pin. Leakage current on this pin should be < 1µA. See the *Block Diagram* for internal pull-up and pull-down resistance. FCM is disabled if the V_{IN} pin is held above 63.5V or if the FB pin is held greater than 8% above the feedback reference voltage. FCM is also disabled during soft-start until the soft-start capacitor is fully charged. When FCM is disabled in these ways, negative inductor current is not allowed and the LT8645SA/LT8646SA operates in pulse-skipping mode.

Spread Spectrum Mode

The LT8645SA/LT8646SA features spread spectrum operation to further reduce EMI emissions. To enable spread spectrum operation, the SYNC/MODE pin should be tied high to INTVCC (or >3V). In this mode, triangular frequency modulation is used to vary the switching frequency between the value programmed by RT to approximately 20% higher than that value. The modulation frequency is approximately 3kHz. For example, when the LT8645SA/LT8646SA is programmed to 2MHz, the frequency will vary from 2MHz to 2.4MHz at a 3kHz rate. When spread spectrum operation is selected, Burst Mode operation is disabled, and the part will run in forced continuous mode.

Synchronization

To synchronize the LT8645SA/LT8646SA oscillator to an external frequency, connect a square wave to the SYNC/MODE pin. The square wave amplitude should have valleys that are below 0.4V and peaks above 1.5V (up to 6V), with a minimum on-time and off-time of 50ns.

The LT8645SA/LT8646SA will not enter Burst Mode operation at low output loads while synchronized to an external clock, but instead will run in FCM to maintain regulation. The LT8645SA/LT8646SA may be synchronized over a 200kHz to 2.2MHz range. The RT resistor should be chosen to set the LT8645SA/LT8646SA switching frequency equal

to or below the lowest synchronization input. For example, if the synchronization signal will be 500kHz and higher, the RT should be selected for 500kHz. The slope compensation is set by the RT value, while the minimum slope compensation required to avoid subharmonic oscillations is established by the inductor size, input voltage, and output voltage. Since the synchronization frequency will not change the slopes of the inductor current waveform, if the inductor is large enough to avoid subharmonic oscillations at the frequency set by RT, then the slope compensation will be sufficient for all synchronization frequencies.

FB Resistor Network

The output voltage is programmed with a resistor divider between the output and the FB pin. Choose the resistor values according to:

$$R1 = R2\left(\frac{V_{OUT}}{0.97V} - 1\right) \quad (1)$$

Reference designators refer to the *Block Diagram*. 1% resistors are recommended to maintain output voltage accuracy.

For the LT8645SA, if low input quiescent current and good light-load efficiency are desired, use large resistor values for the FB resistor divider. The current flowing in the divider acts as a load current, and increases the no-load input current to the converter, which is approximately:

$$I_Q = 1.7\mu A + \left(\frac{V_{OUT}}{R1+R2}\right)\left(\frac{V_{OUT}}{V_{IN}}\right)\left(\frac{1}{n}\right) \quad (2)$$

where 1.7µA is the quiescent current of the LT8645SA and the second term is the current in the feedback divider reflected to the input of the buck operating at its light load efficiency n. For a 3.3V application with R1 = 1M and R2 = 412k, the feedback divider draws 2.3µA. With V_{IN} = 12V and n = 80%, this adds 0.8µA to the 1.7µA quiescent current resulting in 2.5µA no-load current from the 12V supply. Note that this equation implies that the no-load current is a function of V_{IN}; this is plotted in the *Typical Performance Characteristics* section.

When using large FB resistors, a 1pF to 10pF phase-lead capacitor should be connected from V_{OUT} to FB.

Setting the Switching Frequency

The LT8645SA/LT8646SA uses a constant frequency PWM architecture that can be programmed to switch from 200kHz to 2.2MHz by using a resistor tied from the RT pin to ground. A table showing the necessary R_T value for a desired switching frequency is in *Table 1*.

The R_T resistor required for a desired switching frequency can be calculated using:

$$R_T = \frac{46.5}{f_{SW}} - 5.2 \quad (3)$$

where R_T is in kΩ and f_{SW} is the desired switching frequency in MHz.

Table 4. SW Frequency vs RT Value

f_{SW} (MHz)	R_T (kΩ)
0.2	232
0.3	150
0.4	110
0.5	88.7
0.6	71.5
0.7	60.4

0.8	52.3
1.0	41.2
1.2	33.2
1.4	28.0
1.6	23.7
1.8	20.5
2.0	17.8
2.2	15.8

Operating Frequency Selection and Trade-Offs

Selection of the operating frequency is a trade-off between efficiency, component size, and input voltage range. The advantage of high frequency operation is that smaller inductor and capacitor values may be used. The disadvantages are lower efficiency and a smaller input voltage range.

The highest switching frequency ($f_{SW(MAX)}$) for a given application can be calculated as follows:

$$f_{SW(MAX)} = \frac{V_{OUT}+V_{SW(BOT)}}{t_{ON(MIN)}(V_{IN}-V_{SW(TOP)}+V_{SW(BOT)}} \quad (4)$$

where V_{IN} is the typical input voltage, V_{OUT} is the output voltage, $V_{SW(TOP)}$ and $V_{SW(BOT)}$ are the internal switch drops (~0.3V, ~0.2V, respectively at maximum load) and $t_{ON(MIN)}$ is the minimum top switch on-time (see *Table 1*). This equation shows that a slower switching frequency is necessary to accommodate a high V_{IN}/V_{OUT} ratio.

For transient operation, V_{IN} may go as high as the maximum operating rating of 65V regardless of the R_T value; however, the LT8645SA/LT8646SA will reduce switching frequency as necessary to maintain control of inductor current to assure safe operation.

The LT8645SA/LT8646SA is capable of a maximum duty cycle of approximately 98%, and the V_{IN}-to-V_{OUT} dropout is limited by the $R_{DS(ON)}$ of the top switch. In this mode, the LT8645SA/LT8646SA skips switch off-time cycles, resulting in a lower switching frequency than programmed by RT. The maximum top FET on-time that is allowed is ~7µs, after which an off-time will occur on the next f_{sw} clock. When the top FET is turned-off due to this timer, a longer-than-minimum off-time (~170ns) will occur to charge the boost capacitor more strongly.

For applications that cannot allow deviation from the programmed switching frequency at low V_{IN}/V_{OUT} ratios use the following formula to set switching frequency:

$$V_{IN(MIN)} = \frac{V_{OUT}+V_{SW(BOT)}}{1-f_{SW}\bullet t_{OFF(MIN)}} - V_{SW(BOT)} + V_{SW(TOP)} \quad (5)$$

where $V_{IN(MIN)}$ is the minimum input voltage without skipped cycles, V_{OUT} is the output voltage, $V_{SW(TOP)}$ and $V_{SW(BOT)}$ are the internal switch drops (~0.3V, ~0.2V, respectively at maximum load), f_{SW} is the switching frequency (set by RT), and $t_{OFF(MIN)}$ is the minimum switch off-time. Note that a higher switching frequency will increase the minimum input voltage, below which cycles will be dropped to achieve a higher duty cycle.

Inductor Selection and Maximum Output Current

The LT8645SA/LT8646SA is designed to minimize solution size by allowing the inductor to be chosen based on the output load requirements of the application. During overload or short-circuit conditions, the LT8645SA/LT8646SA safely tolerates operation with a saturated inductor through the use of a high speed peak-current mode architecture.

A good first choice for the inductor value is:

$$L = \left(\frac{V_{OUT}+V_{SW(BOT)}}{f_{SW}}\right) \bullet 0.4 \quad (6)$$

where f_{SW} is the switching frequency in MHz, V_{OUT} is the output voltage, $V_{SW(BOT)}$ is the bottom switch drop (~0.2V) and L is the inductor value in µH.

To avoid overheating and poor efficiency, an inductor must be chosen with an RMS current rating that is greater than the maximum expected output load of the application. In addition, the saturation current (typically labeled I_{SAT}) rating of the inductor must be higher than the load current plus 1/2 of in inductor ripple current:

$$I_{L(PEAK)} = I_{LOAD(MAX)} + \frac{1}{2}\Delta I_L \quad (7)$$

where ΔI_L is the inductor ripple current as calculated in Equation 9 and $I_{LOAD(MAX)}$ is the maximum output load for a given application.

As a quick example, an application requiring 2A output should use an inductor with an RMS rating of greater than 2A and an I_{SAT} of greater than 3A. During long duration overload or short-circuit conditions, the inductor RMS rating requirement is greater to avoid overheating of the inductor. To keep the efficiency high, the series resistance (DCR) should be less than 0.02Ω, and the core material should be intended for high frequency applications.

The LT8645SA/LT8646SA limits the peak switch current in order to protect the switches and the system from overload faults. The top switch current limit (I_{LIM}) is 14A at low duty cycles and decreases linearly to 11.5A at DC = 0.9. The inductor value must then be sufficient to supply the desired maximum output current ($I_{OUT(MAX)}$), which is a function of the switch current limit (I_{LIM}) and the ripple current.

$$I_{OUT(MAX)} = I_{LIM} - \frac{\Delta I_L}{2} \quad (8)$$

The peak-to-peak ripple current in the inductor can be calculated as follows:

$$\Delta I_L = \frac{V_{OUT}}{L \bullet f_{SW}} \bullet \left(1 - \frac{V_{OUT}}{V_{IN(MAX)}}\right) \quad (9)$$

where f_{SW} is the switching frequency of the LT8645SA/LT8646SA, and L is the value of the inductor. Therefore, the maximum output current that the LT8645SA/LT8646SA will deliver depends on the switch current limit, the inductor value, and the input and output voltages. The inductor value may have to be increased if the inductor ripple current does not allow sufficient maximum output current ($I_{OUT(MAX)}$) given the switching frequency, and maximum input voltage used in the desired application.

When operating at high V_{IN} (greater than 40V) and at a frequency and duty cycle that would require a switch on-time of less than 100ns, choose an inductor such that the ΔI_L is greater than 1.5A in order to prevent duty cycle jitter.

In order to achieve higher light load efficiency, more energy must be delivered to the output during the single small pulses in Burst Mode operation such that the LT8645SA/LT8646SA can stay in sleep mode longer between each pulse. This can be achieved by using a larger value inductor (i.e., 4.7µH), and should be considered independent of switching frequency when choosing an inductor. For example, while a lower inductor value would typically be used for a high switching frequency application, if high light load efficiency is desired, a higher inductor value should be chosen. See *Figure 15* curve in the Typical Performance Characteristics.

The optimum inductor for a given application may differ from the one indicated by this design guide. A larger value inductor provides a higher maximum load current and reduces the output voltage ripple. For applications requiring smaller load currents, the value of the inductor may be lower and the LT8645SA/LT8646SA may operate with higher ripple current. This allows use of a physically smaller inductor, or one with a lower DCR resulting in higher efficiency. Be aware that low inductance may result in discontinuous mode operation, which further reduces maximum load current.

For more information about maximum output current and discontinuous operation, see Analog Devices' *Application Note 44*.

For duty cycles greater than 50% ($V_{OUT}/V_{IN} > 0.5$), a minimum inductance is required to avoid subharmonic oscillation (See Equation 10). See *Application Note 19* for more details.

$$L_{MIN} = \frac{V_{IN}(2 \bullet DC - 1)}{3 \bullet f_{SW}} \quad (10)$$

where DC is the duty cycle ratio (V_{OUT}/V_{IN}) and f_{SW} is the switching frequency.

Input Capacitors

The V_{IN} of the LT8645SA/LT8646SA should be bypassed with at least three ceramic capacitors for best performance. Two small ceramic capacitors of 0.47µF can be placed close to the part; one on each side of the device (C_{OPT1}, C_{OPT2}). These capacitors should be 0603 or 0805 in size. For automotive applications requiring two series input capacitors, two small 0603 or 0805 may be placed at each side of the LT8645SA/LT8646SA.

A third, larger ceramic capacitor of 4.7µF or larger should be placed close to C_{OPT1} or C_{OPT2}. See the *Low EMI PCB Layout* section for more detail. X7R or X5R capacitors are recommended for best performance across temperature and input voltage variations.

Note that larger input capacitance is required when a lower switching frequency is used. If the input power source has high impedance, or there is significant inductance due to long wires or cables, additional bulk capacitance may be necessary. This can be provided with a low performance electrolytic capacitor.

A ceramic input capacitor combined with trace or cable inductance forms a high quality (under damped) tank circuit. If the LT8645SA/LT8646SA circuit is plugged into a live supply, the input voltage can ring to twice its nominal value, possibly exceeding the LT8645SA/LT8646SA's voltage rating. This situation is easily avoided (see Analog Devices' *Application Note 88*).

Output Capacitor and Output Ripple

The output capacitor has two essential functions. Along with the inductor, it filters the square wave generated by the LT8645SA/LT8646SA to produce the DC output. In this role, it determines the output ripple; thus, low impedance at the switching frequency is important. The second function is to store energy in order to satisfy transient loads and stabilize the LT8645SA/LT8646SA's control loop. Ceramic capacitors have very low equivalent series resistance (ESR) and provide the best ripple performance. For good starting values, see the *Typical Applications* section.

Use X5R or X7R types. This choice provides low output ripple and good transient response. Transient performance can be improved with a higher value output capacitor and the addition of a feedforward capacitor placed between V_{OUT} and FB. Increasing the output capacitance will also decrease the output voltage ripple. A lower value of output capacitor can be used to save space and cost, but transient performance will suffer and may cause loop instability. See the *Typical Applications* in this data sheet for suggested capacitor values.

When choosing a capacitor, special attention should be given to the data sheet to calculate the effective capacitance under the relevant operating conditions of voltage bias and temperature. A physically larger capacitor or one with a higher voltage rating may be required.

Ceramic Capacitors

Ceramic capacitors are small, robust and have very low ESR. However, ceramic capacitors can cause problems when used with the LT8645SA/LT8646SA due to their piezoelectric nature. When in Burst Mode operation, the LT8645SA/LT8646SA's switching frequency depends on the load current, and at very light loads the LT8645SA/LT8646SA can excite the ceramic capacitor at audio frequencies, generating audible noise. Since the LT8645SA/LT8646SA operates at a lower current limit during Burst Mode operation, the noise is typically very quiet to a casual ear. If this is unacceptable, use a high performance tantalum or electrolytic capacitor at the output. Low noise ceramic capacitors are also available.

A final precaution regarding ceramic capacitors concerns the maximum input voltage rating of the LT8645SA/LT8646SA. As previously mentioned, a ceramic input capacitor combined with trace or cable inductance forms a high quality (underdamped) tank circuit. If the LT8645SA/LT8646SA circuit is plugged into a live supply, the input voltage can ring to twice its nominal value, possibly exceeding the LT8645SA/LT8646SA's rating. This situation is easily avoided (see Analog Devices' *Application Note 88*).

Enable Pin

The LT8645SA/LT8646SA is in shutdown when the EN pin is low and active when the pin is high. The rising threshold of the EN comparator is 1.01V, with 45mV of hysteresis. The EN pin can be tied to V_{IN} if the shutdown feature is not used, or tied to a logic level if shutdown control is required.

Adding a resistor divider from V_{IN} to EN programs the LT8645SA/LT8646SA to regulate the output only when V_{IN} is above a desired voltage (see the *Block Diagram*). Typically, this threshold, $V_{IN(EN)}$, is used in situations where the input supply is current limited, or has a relatively high source resistance. A switching regulator draws constant power from the source, so source current increases as source voltage drops. This looks like a negative resistance load to the source and can cause the source to current limit or latch low under low source voltage conditions. The $V_{IN(EN)}$ threshold prevents the regulator from operating at source voltages where the problems might occur. This threshold can be adjusted by setting the values R3 and R4 such that they satisfy the following equation:

$$V_{IN(EN)} = \left(\frac{R3}{R4} + 1\right) \bullet 1.01V \quad (11)$$

where the LT8645SA/LT8646SA will remain off until V_{IN} is above $V_{IN(EN)}$. Due to the comparator's hysteresis, switching will not stop until the input falls slightly below $V_{IN(EN)}$.

When operating in Burst Mode operation for light load currents, the current through the $V_{IN(EN)}$ resistor network can easily be greater than the supply current consumed by the LT8645SA/LT8646SA. Therefore, the $V_{IN(EN)}$ resistors should be large to minimize their effect on efficiency at low loads.

$INTV_{CC}$ Regulator

An internal low dropout (LDO) regulator produces the 3.4V supply from V_{IN} that powers the drivers and the internal bias circuitry. The INTVCC can supply enough current for the LT8645SA/LT8646SA's circuitry. To improve efficiency the internal LDO can also draw current from the BIAS pin when the BIAS pin is at 3.1V or higher. Typically the BIAS pin can be tied to the output of the LT8645SA/LT8646SA, or can be tied to an external supply of 3.3V or above. If BIAS is connected to a supply other than V_{OUT}, be sure to bypass with a local ceramic capacitor. If the BIAS pin is below 3.0V, the internal LDO will consume current from V_{IN}. Applications with high input voltage and high switching

frequency where the internal LDO pulls current from V_{IN} will increase die temperature because of the higher power dissipation across the LDO. Do not connect an external load to the INTVCC pin.

Frequency Compensation (LT8646SA Only)

Loop compensation determines the stability and transient performance, and is provided by the components tied to the V_C pin. Generally, a capacitor (C_C) and a resistor (R_C) in series to ground are used. Designing the compensation network is a bit complicated and the best values depend on the application. A practical approach is to start with one of the circuits in this data sheet that is similar to the application and tune the compensation network to optimize the performance. LTspice® or LTpowerCAD simulations can help in this process. Stability should then be checked across all operating conditions, including load current, input voltage and temperature. The LT1375 data sheet contains a more thorough discussion of loop compensation and describes how to test the stability using a transient load.

Figure 60 shows an equivalent circuit for the LT8646SA control loop. The error amplifier is a transconductance amplifier with finite output impedance. The power section, consisting of the modulator, power switches, and inductor, is modeled as a transconductance amplifier generating an output current proportional to the voltage at the V_C pin. Note that the output capacitor integrates this current, and that the capacitor on the V_C pin (C_C) integrates the error amplifier output current, resulting in two poles in the loop. A zero is required and comes from a resistor R_C in series with C_C. This simple model works well as long as the value of the inductor is not too high and the loop crossover frequency is much lower than the switching frequency. A phase lead capacitor (C_{PL}) across the feedback divider can be used to improve the transient response and is required to cancel the parasitic pole caused by the feedback node to ground capacitance.

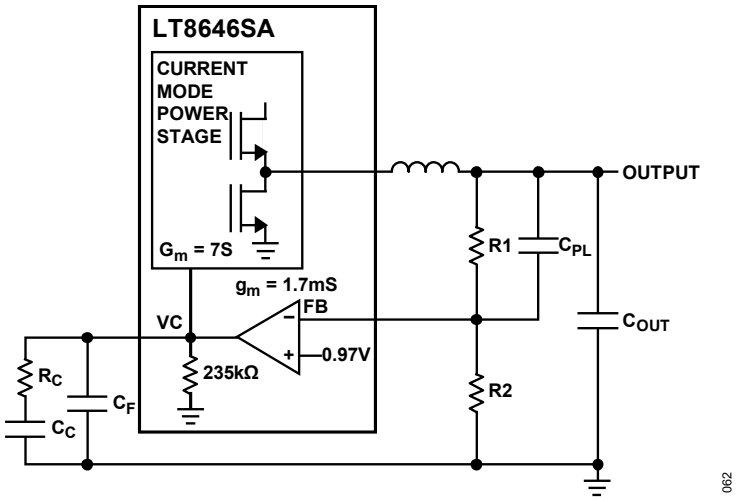


Figure 60. Model for Loop Response

Output Voltage Tracking and Soft-Start

The LT8645SA/LT8646SA allows the user to program its output voltage ramp rate by means of the TR/SS pin. An internal 2µA pulls up the TR/SS pin to $INTV_{CC}$. Putting an external capacitor on TR/SS enables soft starting the output to prevent current surge on the input supply. During the softstart ramp the output voltage will proportionally track the TR/SS pin voltage.

For output tracking applications, TR/SS can be externally driven by another voltage source. For the LT8645SA, from 0V to 0.97V, the TR/SS voltage will override the internal 0.97V reference input to the error amplifier, thus regulating the FB pin voltage to that of TR/SS pin. When TR/SS is above 0.97V, tracking is disabled and the feedback voltage will regulate to the internal reference voltage. For the LT8646SA, from 0V to 1.6V, the TR/SS voltage will override the

internal 0.97V reference input to the error amplifier, thus regulating the FB pin voltage to a function of the TR/ SS pin. See plot in the *Typical Performance Characteristics* section. When TR/SS is above 1.6V, tracking is disabled and the feedback voltage will regulate to the internal reference voltage. The TR/SS pin may be left floating if the function is not needed.

An active pull-down circuit is connected to the TR/SS pin, which will discharge the external soft-start capacitor in the case of fault conditions and restart the ramp when the faults are cleared. Fault conditions that clear the soft-start capacitor are the EN/UV pin transitioning low, V_{IN} voltage falling too low, or thermal shutdown.

Output Power Good

When the LT8645SA/LT8646SA's output voltage is within the ±8% window of the regulation point, the output voltage is considered good and the open-drain PG pin goes high impedance and is typically pulled high with an external resistor. Otherwise, the internal pull-down device pulls the PG pin low. To prevent glitching both the upper and lower thresholds include 0.4% of hysteresis. PG is valid when V_{IN} is above 3.4V.

The PG pin is also actively pulled low during several fault conditions: EN/UV pin is below 1V, $INTV_{CC}$ has fallen too low, V_{IN} is too low, or thermal shutdown.

Paralleling (LT8646SA Only)

To increase the possible output current, two LT8646SAs can be connected in parallel to the same output. To do this, the V_C and FB pins are connected together, and each LT8646SA's SW node is connected to the common output through its own inductor. The CLKOUT pin of one LT8646SA should be connected to the SYNC/MODE pin of the second LT8646SA to have both devices operate in the same mode. During FCM, Spread Spectrum, and Synchronization modes, both devices will operate at the same frequency, 180° out of phase with each other. *Figure 61* shows an application where two LT8646SA are paralleled to get one output capable of up to 16A.

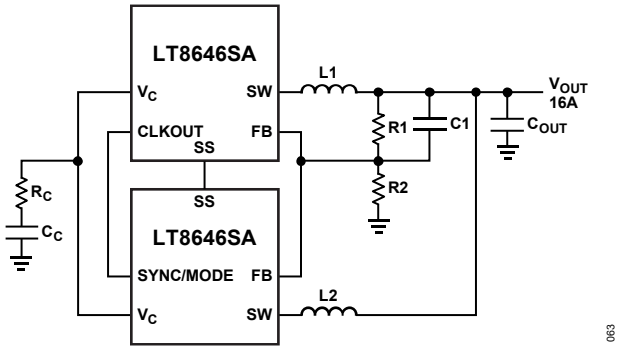


Figure 61. Paralleling Two LT8646SA

Shorted and Reversed Input Protection

The LT8645SA/LT8646SA tolerates a shorted output. The bottom switch current is monitored such that if inductor current is beyond safe levels switching of the top switch will be delayed until such time as the inductor current falls to safe levels.

There is another situation to consider in systems where the output will be held high when the input to the LT8645SA/LT8646SA is absent. This may occur in battery charging applications or in battery-backup systems where a battery or some other supply is diode ORed with the LT8645SA/LT8646SA's output. If the V_{IN} pin is allowed to float and the EN pin is held high (either by a logic signal or because it is tied to V_{IN}), then the LT8645SA/LT8646SA's internal circuitry will pull its quiescent current through its SW pin. This is acceptable if the system can tolerate current draw in this

state. If the EN pin is grounded the SW pin current will drop to near 1µA. However, if the V_{IN} pin is grounded while the output is held high, regardless of EN, parasitic body diodes inside the LT8645SA/LT8646SA can pull current from the output through the SW pin and the V_{IN} pin. *Figure 62* shows a connection of the V_{IN} and EN/UV pins that will allow the LT8645SA/LT8646SA to run only when the input voltage is present and that protects against a shorted or reversed input.

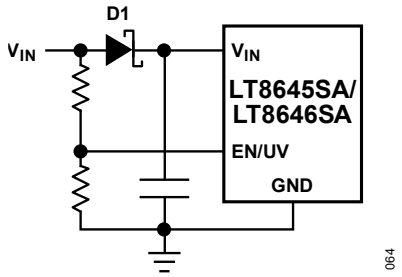


Figure 62. Reverse V_{IN} Protection

Thermal Considerations

For higher ambient temperatures, care should be taken in the layout of the PCB to ensure good heat sinking of the LT8645SA/LT8646SA. The ground pins on the bottom of the package should be soldered to a ground plane. This ground should be tied to large copper layers below with thermal vias; these layers will spread heat dissipated by the LT8645SA/LT8646SA. Placing additional vias can reduce thermal resistance further. The maximum load current should be derated as the ambient temperature approaches the maximum junction rating. Power dissipation within the LT8645SA/LT8646SA can be estimated by calculating the total power loss from an efficiency measurement and subtracting the inductor loss. The die temperature is calculated by multiplying the LT8645SA/LT8646SA power dissipation by the thermal resistance from junction to ambient.

The internal overtemperature protection monitors the junction temperature of the LT8645SA/LT8646SA. If the junction temperature reaches approximately 180°C, the LT8645SA/LT8646SA will stop switching and indicate a fault condition until the temperature drops about 10°C cooler.

Temperature rise of the LT8645SA/LT8646SA is worst when operating at high load, high V_{IN}, and high switching frequency. If the case temperature is too high for a given application, then either V_{IN}, switching frequency, or load current can be decreased to reduce the temperature to an acceptable level. *Figure 63* shows examples of how case temperature rise can be managed by reducing V_{IN}, switching frequency, or load.

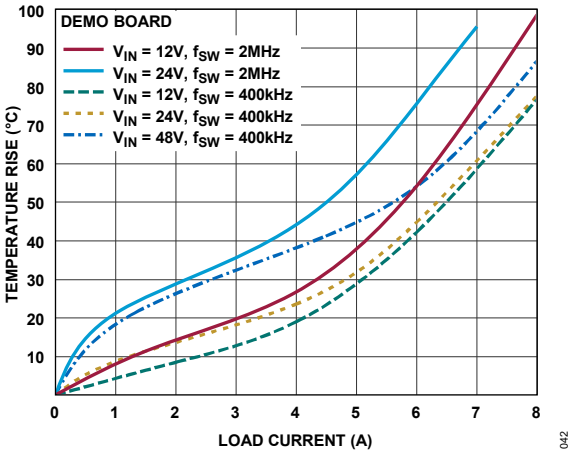


Figure 63. Case Temperature Rise

The LT8645SA/LT8646SA's top switch current limit decreases with higher duty cycle operation for slope compensation. This also limits the output current the LT8645SA/LT8646SA can deliver for a given application. See the curve in the *Typical Performance Characteristics* section.

TYPICAL APPLICATIONS

PINS NOT USED IN THIS CIRCUIT: BST, $INTV_{CC}$

[1] V_C PIN AND COMPONENTS ONLY APPLY TO LT8646SA.

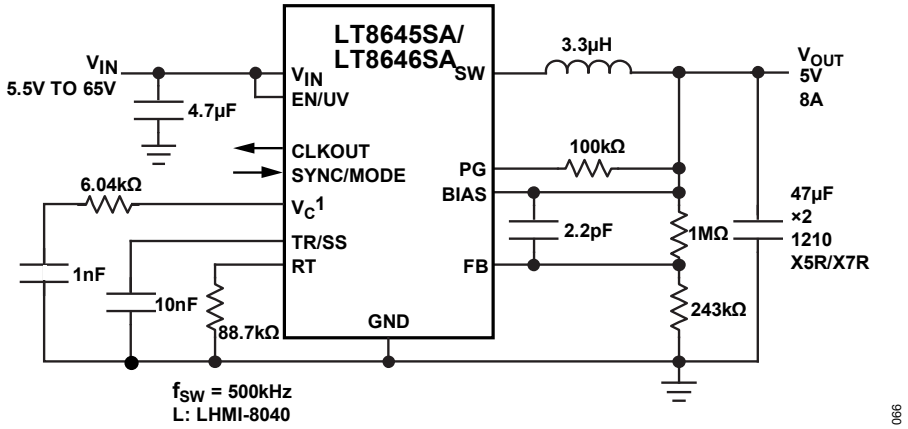


Figure 64. 5V 8A Step-Down Converter with Soft-Start and Power Good

PINS NOT USED IN THIS CIRCUIT: BST, $INTV_{CC}$

[1] V_C PIN AND COMPONENTS ONLY APPLY TO LT8646SA.

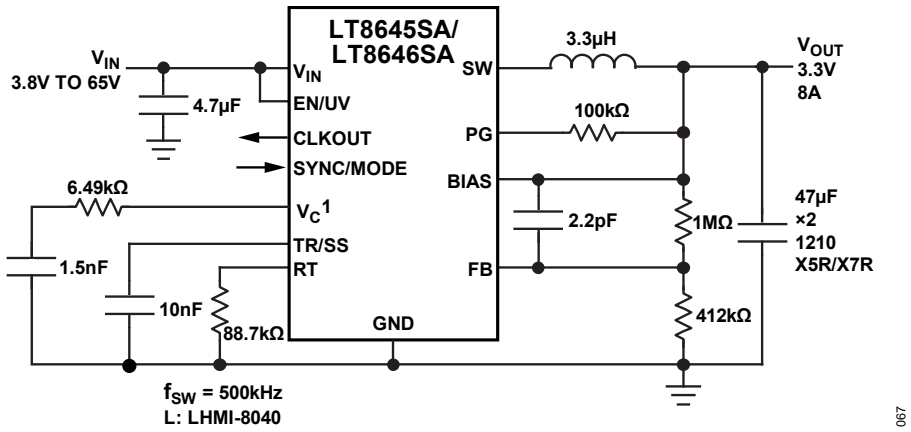


Figure 65. 3.3V, 8A Step-Down Converter with Soft-Start and Power Good

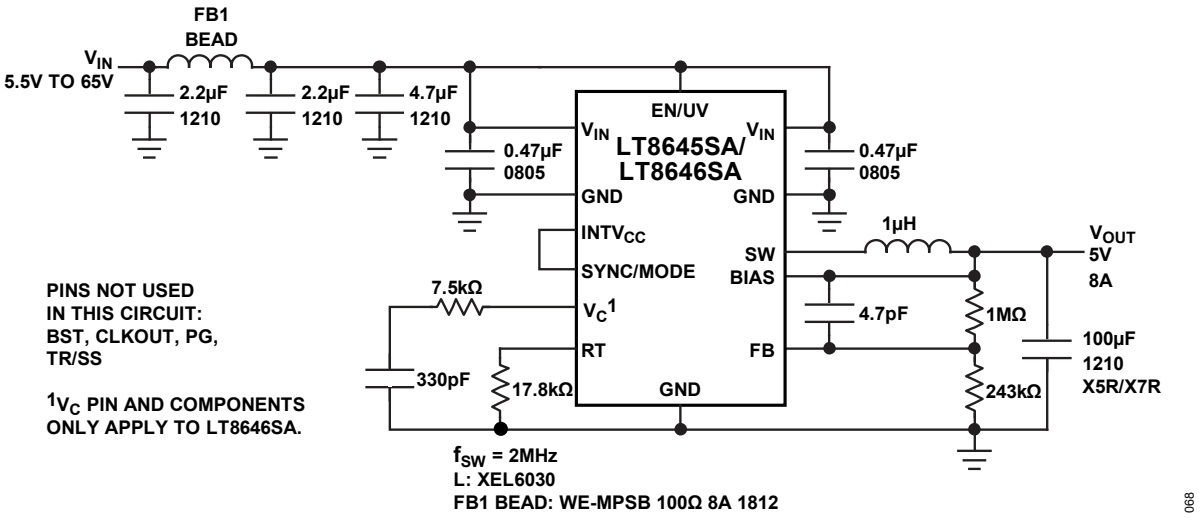


Figure 66. Ultralow EMI 5V, 8A Step-Down Converter with Spread Spectrum

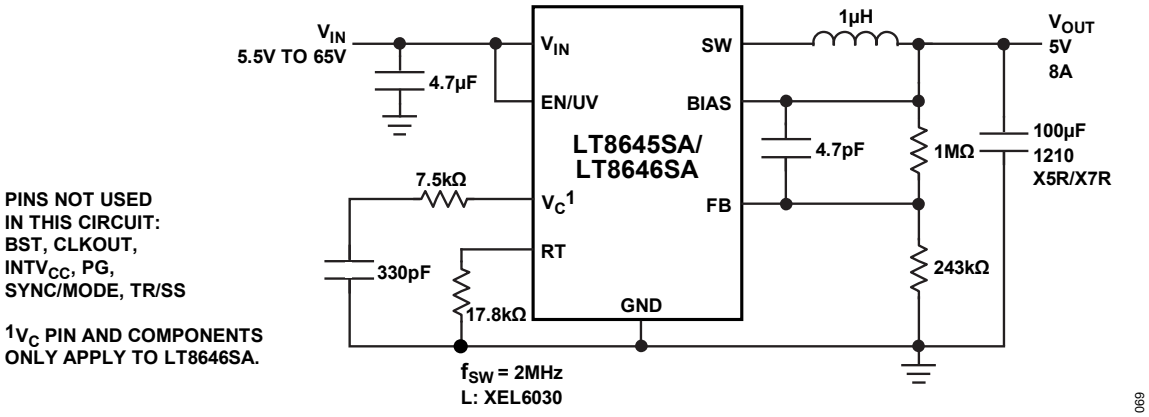


Figure 67. 2MHz 5V, 8A Step-Down Converter

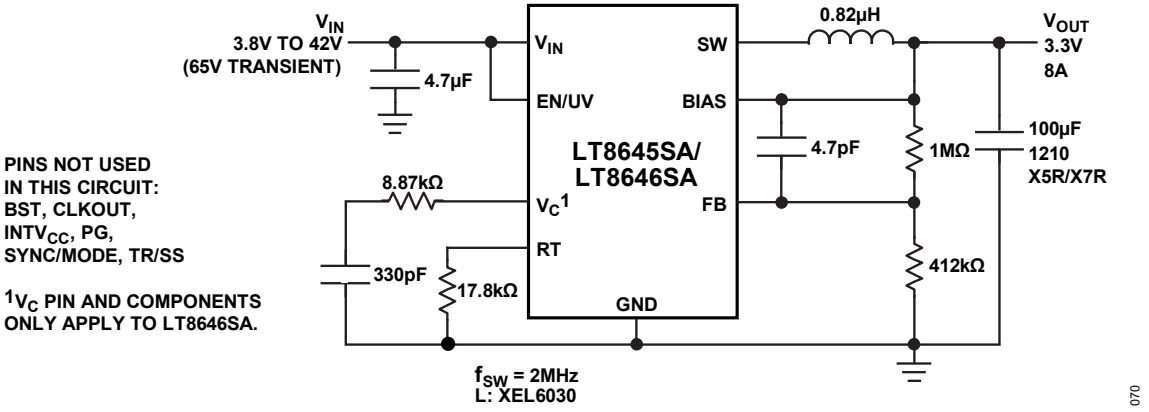


Figure 68. 2MHz 3.3V, 8A Step-Down Converter

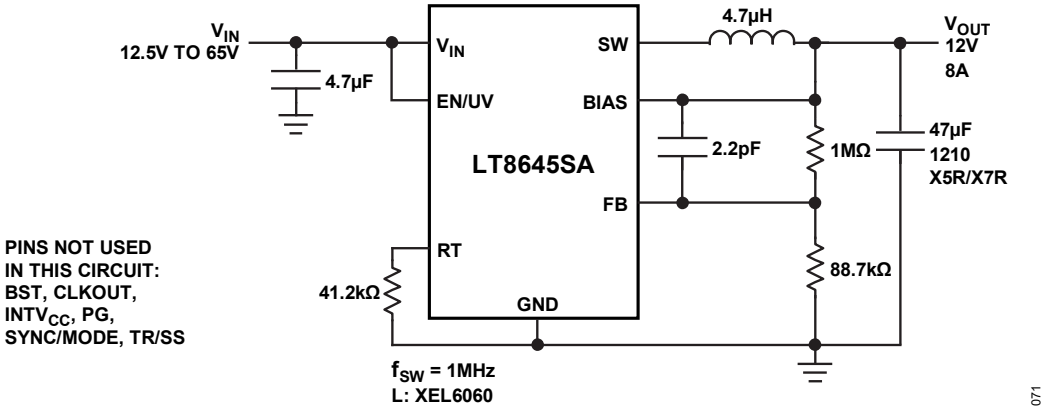


Figure 69. 12V, 8A Step-Down Converter

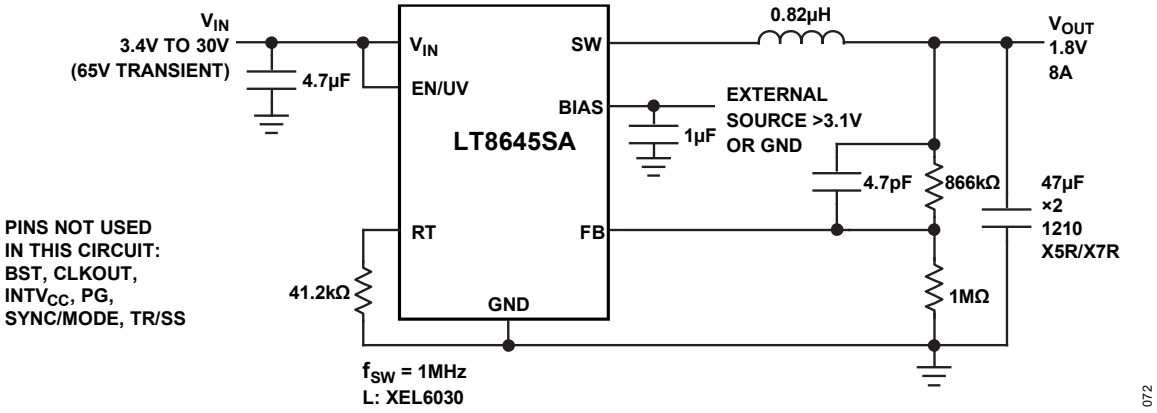


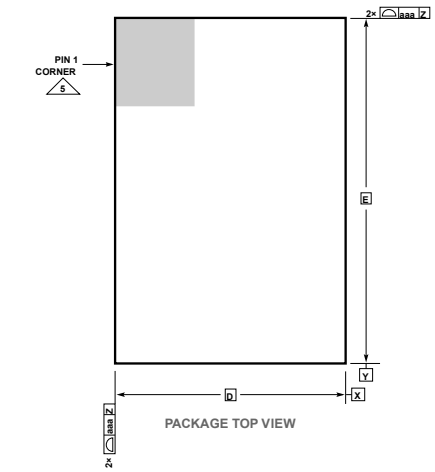
Figure 70. 1.8V, 8A Step-Down Converter

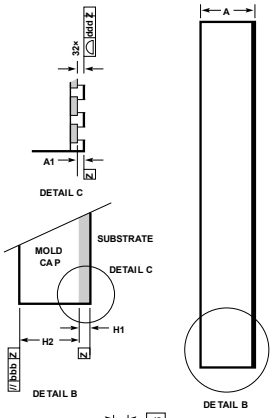
RELATED PARTS

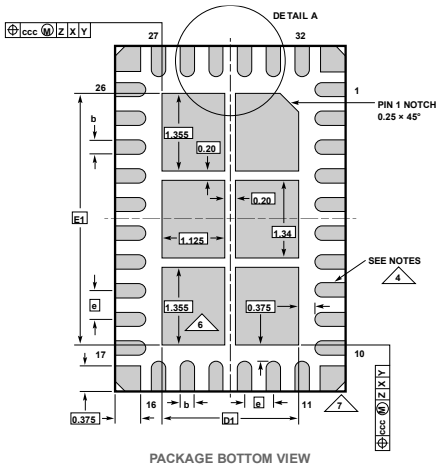
PART NUMBER	DESCRIPTION	COMMENTS
LT8645S/LT8646S	65V, 8A, Synchronous Step-Down Silent Switcher 2 with I_Q = 2.5µA	$V_{IN(MIN)}$ = 3.4V, $V_{IN(MAX)}$ = 65V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, 6mm × 4mm LQFN-32
LT8640SA/LT8643SA	42V, 6A Synchronous Step-Down Silent Switcher 2 with 2.5µA Quiescent Current	$V_{IN(MIN)}$ = 3.4V, $V_{OUT(MAX)}$ = 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, 4mm × 4mm LQFN-24
LT8640A	42V, 5A/8A Peak Synchronous Step-Down Silent Switcher with 2.5µA Quiescent Current	$V_{IN(MIN)}$ = 3.4V, $V_{IN(MAX)}$ = 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, 3mm × 4mm QFN-18
LT8641A	65V, 3.5A/5A Peak Synchronous Step-Down Silent Switcher with 2.5µA Quiescent Current	$V_{IN(MIN)}$ = 3V, $V_{IN(MAX)}$ = 65V, $V_{OUT(MIN)}$ = 0.81V, I_Q = 2.5µA, I_{SD} < 1µA, 3mm × 4mm QFN-18
LT8609/LT8609A	42V, 2A, 94% Efficiency, 2.2MHz Synchronous MicroPower Step-Down DC/DC Converter with I_Q = 2.5µA	$V_{IN(MIN)}$ = 3V, $V_{IN(MAX)}$ = 42V, $V_{OUT(MIN)}$ = 0.8V, I_Q = 2.5µA, I_{SD} < 1µA, MSOP-10E
LT8620	65V, 2.5A, 94% Efficiency, 2.2MHz Synchronous MicroPower Step-Down DC/DC Converter with I_Q = 2.5µA	$V_{IN(MIN)}$ = 3.4V, $V_{IN(MAX)}$ = 65V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, MSOP-16E, 3mm × 5mm QFN-24

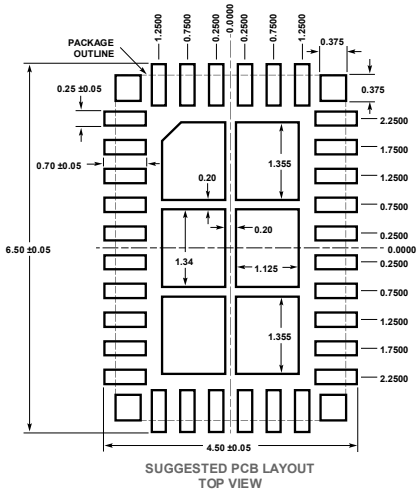
OUTLINE DIMENSIONS

LQFN Package
32-Lead (6mm x 4mm x 0.94mm)
(Reference LTC DWG # 05-08-1512 Rev C)



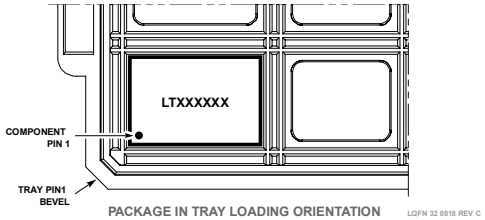






DIMENSIONS				
SYMBOL	MIN	NOM	MAX	NOTES
A	0.85	0.94	1.03	
A1	0.01	0.02	0.03	
L	0.30	0.40	0.50	
b	0.22	0.25	0.28	
D		4.00		
E		6.00		
D1		2.45		
E1		4.45		
e		0.50		
H1		0.24 REF		SUBSTRATE THK
H2		0.70 REF		MOLD CAP HT
aaa			0.10	
bbb			0.10	
ccc			0.10	
ddd			0.10	
eee			0.15	
fff			0.08	

NOTES:
1. DIMENSIONING AND TOLERANCING PER ASMEY 14.5M-1994
2. ALL DIMENSIONS ARE IN MILLIMETERS
3. PRIMARY DATUM -Z- IS SEATING PLANE
4. METAL FEATURES UNDER THE SOLDER MASK OPENING NOT SHOWN SO AS NOT TO OBSCURE THESE TERMINALS AND HEAT FEATURES
5. DETAILS OF PIN 1 IDENTIFIER ARE OPTIONAL, BUT MUST BE LOCATED WITHIN THE ZONE INDICATED.THE PIN1 IDENTIFIER MAY BE EITHER A MOLD OR MARKED FEATURE
6. THE EXPOSED HE AT FEATURE IS SEGMENTED AND ARRANGED IN A MATRIX FORM AT. IT MAY HAVE OPTIONA L CORNER RADII ON EACH SEGMENT
7. CORNER SUPPORT PAD CHAMFER IS OPTIONAL



ORDERING GUIDE

Table 5. Ordering Guide

PART NUMBER	TAPE AND REEL	PART MARKING*	FINISH CODE	PAD FINISH	PACKAGE TYPE***	MSL RATING	TEMPERATURE RANGE
LT8645SAAV#PBF	LT8645SAAV#TRPBF	8645SAV	e4	Au (RoHS)	LQFN (Laminate Package with QFN Footprint)	3	–40°C to 125°C
LT8646SAAV#PBF	LT8646SAAV#TRPBF	8646SAV	e4	Au (RoHS)	LQFN (Laminate Package with QFN Footprint)	3	–40°C to 125°C
AUTOMOTIVE PRODUCTS**							
LT8645SAAV#WPBF	LT8645SAAV#WTRPBF	8645SAV	e4	Au (RoHS)	LQFN (Laminate Package with QFN Footprint)	3	–40°C to 125°C
LT8646SAAV#WPBF	LT8646SAAV#WTRPBF	8646SAV	e4	Au (RoHS)	LQFN (Laminate Package with QFN Footprint)	3	–40°C to 125°C

Contact the factory for parts specified with wider operating temperature ranges. *The temperature grade is identified by a label on the shipping container.

Tape and reel specifications. Some packages are available in 500 unit reels through designated sales channels with #TRMPBF suffix.

**Versions of this part are available with controlled manufacturing to support the quality and reliability requirements of automotive applications. These models are designated with a #W suffix. Only the automotive grade products shown are available for use in automotive applications. Contact your local Analog Devices account representative for specific product ordering information and to obtain the specific Automotive Reliability reports for these models.