42V, 3.5A Synchronous Step-down Regulator with 2.5µA Quiescent Current

FEATURES

- **Wide Input Voltage Range: 3V to 42V**
- **Wide Output Voltage Range: 0.787V to (V_{IN} – 0.4V)**
- **Ultralow Quiescent Current Burst Mode® Operation:**
  - **<2.5µA I_Q Regulating 12V_{IN} to 3.3V_{OUT}**
  - **Output Ripple <10mV_{P-P}**
- **Silent Switcher® Powertrain for Ultralow EMI Emissions**
- **High Efficiency 2MHz Synchronous Operation:**
  - **Up to 93% Efficiency at 2MHz, 12V_{IN} to 5V_{OUT}**
- **Fast Minimum Switch-On Time: 40ns**
- **Very Low Dropout: 125mV at 1A**
- Adjustable and Synchronizable: 400kHz to 2.5MHz
- Optional Spread-Spectrum Frequency Modulation
- Fixed Frequency Peak Current-Mode Operation
- Accurate 1V Enable Pin Threshold
- Output Soft-Start and Tracking
- Small 3mm × 3mm Side Wettable QFN Package
  - Clearance Between High Voltage and Low Voltage Pins
  - Excellent Solder Joint Reliability
- AEC-Q100 Qualified for Automotive Applications
  - Temperature Grade 0: −40°C to +150°C, T_A

GENERAL DESCRIPTION

The **LT®8615** is a compact, high efficiency, high speed synchronous monolithic step-down switching regulator that can deliver 3.5A of continuous current. The LT8615's ultralow 2.5µA quiescent current in Burst Mode operation (with the output in full regulation) enables high efficiency down to very low load currents while keeping the output ripple below 10mV_{P-P}.

A SYNC pin allows synchronization to an external clock or spread-spectrum modulation for low EMI operation. Internal compensation with peak current-mode topology allows the use of small inductors and results in fast transient response and good loop stability. The EN/UV pin has an accurate 1V threshold and can be used to program V_{IN} UVLO or to shut down the part. A capacitor on the TR/SS pin programs the output voltage ramp rate during start-up. An open-drain PG pin flag signals when the output is within ±8% as well as fault conditions.

APPLICATIONS

- Automotive and Industrial Supplies
- Low EMI Step-Down

TYPICAL APPLICATION

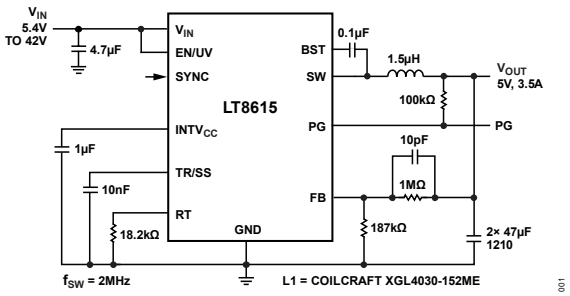

Figure 1. 5V, 3.5A Step-Down Converter

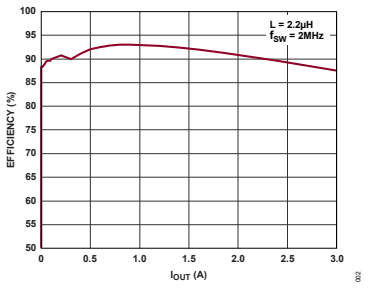

Figure 2. 12V_{IN} to 5V_{OUT} Efficiency

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REVISION HISTORY

REVISION	DATE	DESCRIPTION	PAGE NUMBER
0	10/24	Initial Release	—
A	06/25	Updated the minimum value of the Feedback Pin Input Current section in the EC table	4

SPECIFICATIONS

Table 1. Electrical Characteristics

(T_J = -40°C to +150°C, unless otherwise noted. Typical values are at T_A. = 25°C. All voltages are referenced to GND, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS/COMMENTS	MIN	TYP	MAX	UNITS
Minimum Input Voltage	V_{IN}			2.5	3.0	V
V_{IN} Quiescent Current in Shutdown	$I_{Q(SHDN)}$	$V_{EN/UV}$ = 0V, V_{SYNC} = 0V, T_A = +25°C		1	4	µA
V_{IN} Quiescent Current in Sleep	I_Q	$V_{EN/UV}$ = 2V, Not Switching, V_{SYNC} = 0V, T_A = +25°C		1.7	5.0	µA
		$V_{EN/UV}$ = 2V, Not Switching, V_{SYNC} = 0V		1.7	12.0	
V_{IN} Current in Regulation	I_{IN}	V_{IN} = 6V, V_{OUT} = 2.7V, Output Load = 1mA, Burst Mode		540	700	µA
Feedback Reference Voltage	V_{FB}	V_{IN} = 6V, I_{LOAD} = 200mA, T_A = +25°C	0.783	0.787	0.791	V
		V_{IN} = 6V, I_{LOAD} = 200mA	0.771	0.787	0.801	
Feedback Voltage Line Regulation	$\Delta V_{FB(LINE)}$	V_{IN} = 4V to 40V		0.005	0.020	%/V
Feedback Pin Input Current	I_{FB}	V_{FB} = 1V	-20		20	nA
Minimum On-Time	$t_{ON(MIN)}$	I_{LOAD} = 1.6A, SYNC = 0V		40	75	ns
		I_{LOAD} = 1.6A, SYNC = 1.9V		40	60	
Minimum Off-Time	$t_{OFF(MIN)}$			75	100	ns
Oscillator Frequency	f_{sw}	RT = 221kΩ, I_{LOAD} = 0.5A	170	200	230	kHz
		RT = 60.4kΩ, I_{LOAD} = 0.5A	640	700	760	
		RT = 18.2kΩ, I_{LOAD} = 0.5A	1925	2000	2075	
Top Power NMOS On-Resistance	R_{TOP}	I_{SW} = 1A		80		mΩ
Top Power NMOS Current Limit	$I_{PEAK-LIMIT}$		6.0	7.3	8.5	A
Bottom Power NMOS On-Resistance	R_{BOT}			80		mΩ
SW Leakage Current	I_{SW-LKG}	V_{IN} = 42V, V_{SW} = 0V, 42V	-15		15	µA

(T_J = -40°C to +150°C, unless otherwise noted. Typical values are at T_A. = 25°C. All voltages are referenced to GND, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS/COMMENTS	MIN	TYP	MAX	UNITS
EN/UV Pin Threshold	V_{EN}	EN/UV Rising	0.99	1.05	1.11	V
		EN/UV Hysteresis		50		mV
EN/UV Pin Current	I_{EN}	$V_{EN/UV}$ = 2V		400		nA
PG Upper Threshold Offset from V_{FB}	PGH	V_{FB} Rising	5.0	7.5	10.0	%
PG Lower Threshold Offset from V_{FB}	PGL	V_{FB} Falling	5.5	8.0	10.5	%
PG Hysteresis	PG_{HYS}			0.5		%
PG Leakage	I_{PG-LKG}	V_{PG} = 42V	-200		+200	nA
PG Pull-Down Resistance	R_{PG}	V_{PG} = 0.1V		500	1200	Ω
SYNC Threshold	V_{SYNC}	SYNC DC and Clock Low Level Voltage	0.4	0.9		V
		SYNC Clock High Level Voltage		1.3	1.5	
		SYNC DC High Level Voltage	2.2	2.7	3.2	
TR/SS Source Current	I_{SS}		1.0	2.5	4.0	µA
TR/SS Pull-Down Resistance	R_{SS}	Fault Condition, TR/SS = 0.1V, T_A = +25°C		300	900	Ω
Spread-Spectrum Modulation Frequency	f_{SSFM}	V_{SYNC} = 3.3V, T_A = +25°C	1	3	6	kHz

ABSOLUTE MAXIMUM RATINGS [1]

T_A = 25°C, unless otherwise specified.

Table 2. Absolute Maximum Ratings

PARAMETER	RATING
V_{IN}, EN/UV, PG	−0.3V to 42V
TR/SS, $INTV_{CC}$, RT, FB	−0.3V to 4V
SYNC	−0.3V to 6V
Operating Junction Temperature Range [2, 4], LT8615R	–40°C to +150°C
Storage Temperature Range	–65°C to +150°C

1 Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime. Absolute Maximum Ratings are those values beyond which the life of a device may be impaired.

2 The LT8615R is specified over the –40°C to 150°C operating junction temperature range. High junction temperatures degrade operating lifetimes; operating lifetime is derated for junction temperatures greater than 125°C. Note that the maximum ambient temperature consistent with these specifications is determined by specific operating conditions in conjunction with the board layout, rated package thermal impedance, and other environmental factors.

The junction temperature (TJ, in °C) is calculated from the ambient temperature (TA, in °C) and power dissipation (PD, in Watts) according to the formula:

TJ = TA + (PD × θJA)

where, θJA (in °C/W) is the package thermal impedance.

3 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.

4 This IC includes overtemperature protection intended to protect the device during overload conditions. Junction temperature exceeds 150°C when overtemperature protection is active. Continuous operation above the specified maximum operating junction temperature reduces lifetime.

PIN CONFIGURATIONS AND FUNCTION DESCRIPTIONS

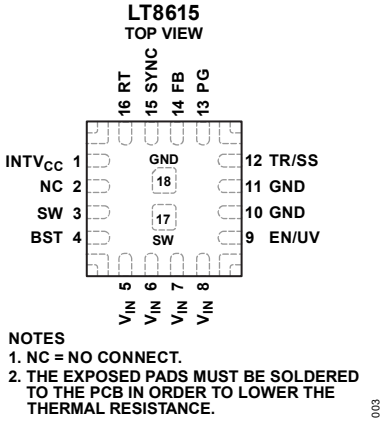


Figure 3. Pin Configuration

16-LEAD (3mm × 3mm) PLASTIC QFN
DEMO BOARD: θ_{JA} = 32°C/W, Ψ_{JT} = 1.2°C/W (3)
JEDEC BOARD: θ_{JCTOP} = 51.8°C/W, $\theta_{JCBOTTOM}$ = 7.7°C/W

Table 3. Pin Descriptions

PIN	NAME	DESCRIPTION
1	$INTV_{CC}$	Internal 3.5V Regulator Bypass Pin. The internal power drivers and control circuits are powered from this voltage. $INTV_{CC}$ max. output current is 20mA. Voltage on $INTV_{CC}$ varies between 2.8V and 3.5V. Decouple this pin to power ground with at least a 1µF low ESR ceramic capacitor. Do not load the $INTV_{CC}$ pin with external circuitry.
2	NC	No Connect.
3, Exposed Pad Pin 17	SW	The SW pin is the output of the internal power switches. Connect this pin to the inductor and boost capacitor. This node should be kept small on the PCB for good performance. The exposed pad should be soldered to the PCB for good thermal performance.
4	BST	This pin is used to provide a drive voltage, higher than the input voltage, to the topside power switch. Place a 0.1µF boost capacitor as close as possible to the IC. Do not place a resistor in series with this pin.
5 to 8	V_{IN}	The V_{IN} pin supplies current to the LT8615 internal circuitry and to the internal topside power switch. This pin must be locally bypassed. 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
9	EN/UV	The LT8615 is shut down when this pin is low and active when this pin is high. The hysteretic threshold voltage is 1.05V going up and 1.00V 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 LT8615 shuts down.

10 to 11, Exposed Pad Pin 18	GND	Ground. Place the negative terminal of the input capacitor as close to the GND pins as possible. The exposed pad should be soldered to the PCB for good thermal performance.
12	TR/SS	Output Tracking and Soft-Start Pin. This pin allows user control of output voltage ramp rate during start-up. A TR/SS voltage below 0.787V forces the LT8615 to regulate the FB pin to equal the TR/SS pin voltage. When TR/SS is above 0.787V, 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 a 300Ω MOSFET during shutdown and fault conditions; use a series resistor if driving from a low impedance output.
13	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 valid when V_{IN} is above 3V, regardless of EN/UV pin state.
14	FB	The LT8615 regulates the FB pin to 0.787V. Connect the feedback resistor divider tap to this pin. Also, connect a phase lead capacitor between FB and V_{OUT}. Typically, this capacitor is 4.7pF to 22pF.
15	SYNC	External Clock Synchronization Input. Ground this pin for low ripple Burst Mode operation at low output loads. Tie to a clock source for synchronization to an external frequency. Leave floating for pulse-skipping mode with no spread-spectrum modulation. Tie to $INTV_{CC}$ or tie to a voltage between 3.2V and 5.0V for pulse-skipping mode with spread-spectrum modulation. When in pulse-skipping mode, the I_Q increases to several mA.
16	RT	A resistor is tied between RT and ground to set the switching frequency.

TYPICAL PERFORMANCE CHARACTERISTICS

T_A = 25°C, unless otherwise noted.

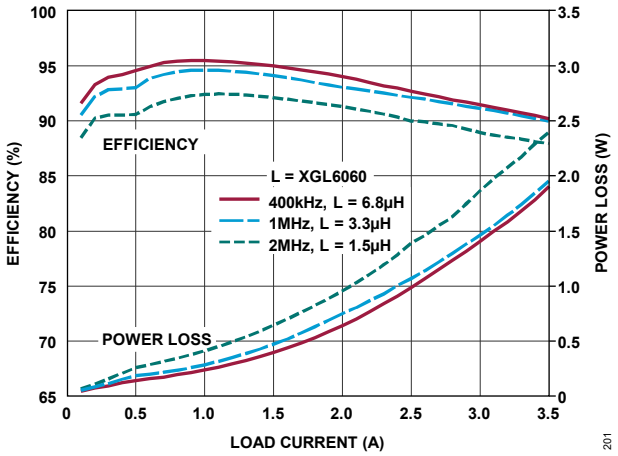


Figure 4. $12V_{IN}$ to $5V_{OUT}$ Efficiency vs. Frequency

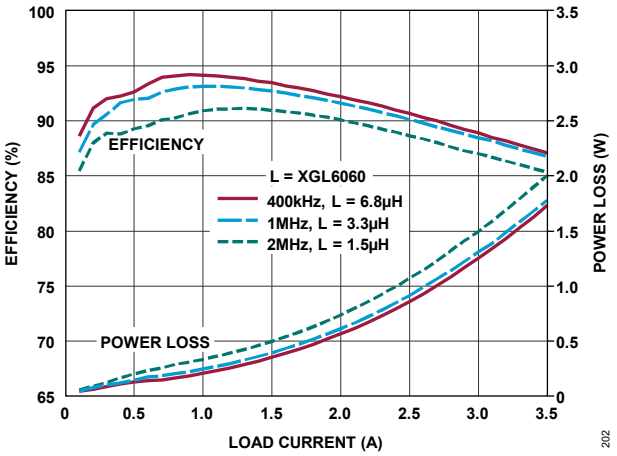


Figure 5. $12V_{IN}$ to $3.3V_{OUT}$ Efficiency vs. Frequency

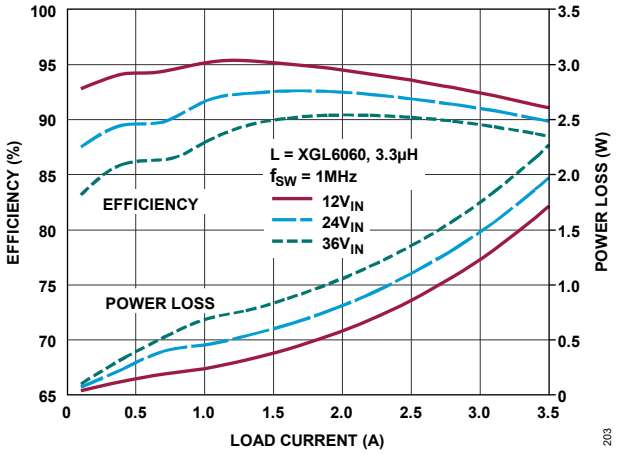


Figure 6. Efficiency at $5V_{OUT}$

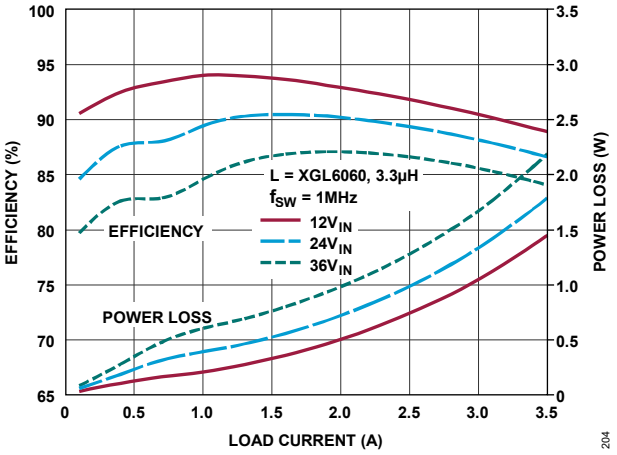


Figure 7. Efficiency at $3.3V_{OUT}$

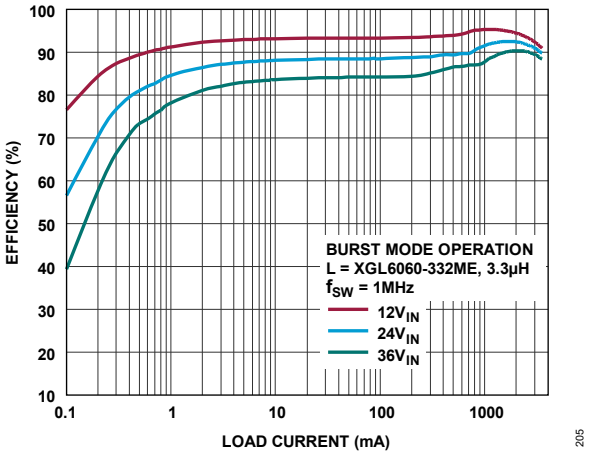


Figure 8. Light Load Efficiency at $5V_{OUT}$

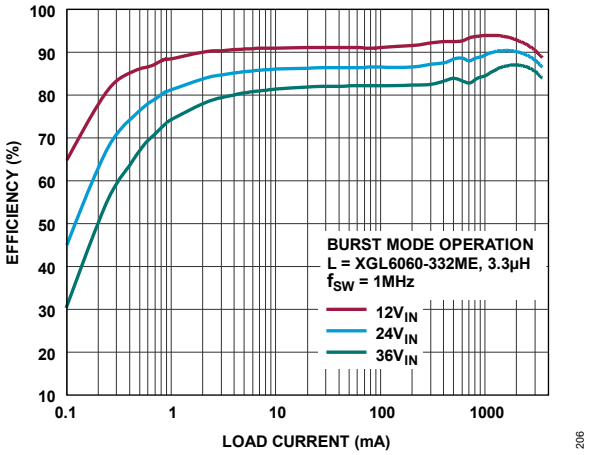


Figure 9. Light Load Efficiency at $3.3V_{OUT}$

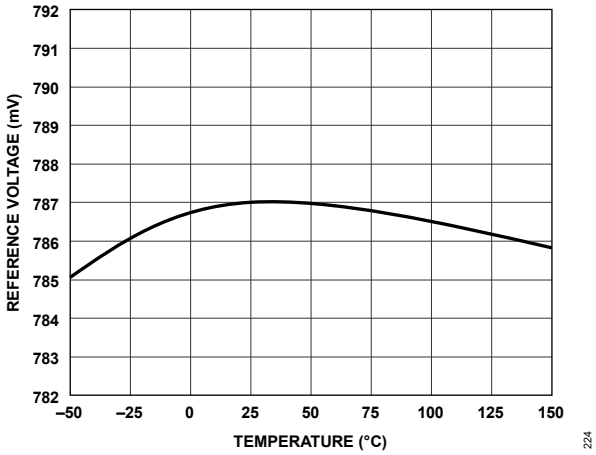


Figure 10. Feedback Reference Voltage

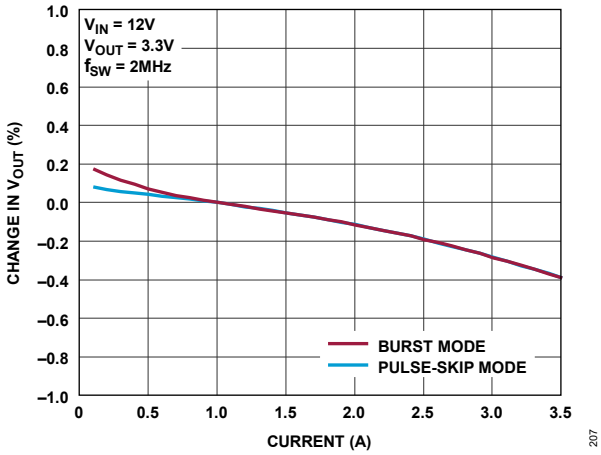


Figure 11. Load Regulation

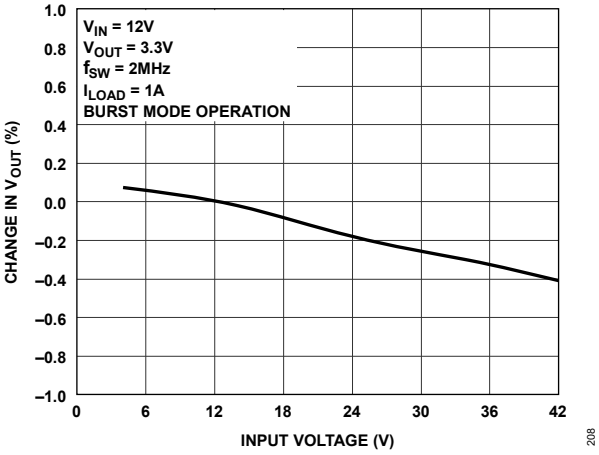


Figure 12. Line Regulation

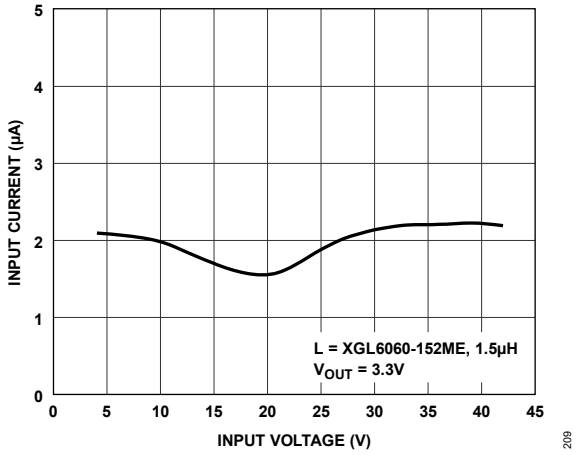


Figure 13. No-Load Supply Current in Regulation

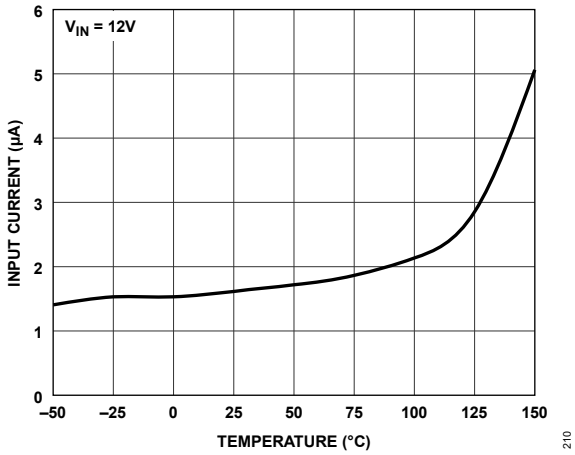


Figure 14. No-Load Supply Current vs. Temperature (Not Switching)

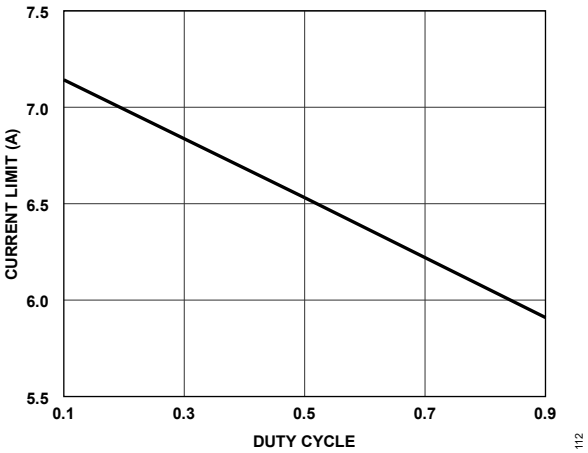


Figure 15. Top FET Current Limit vs Duty Cycle

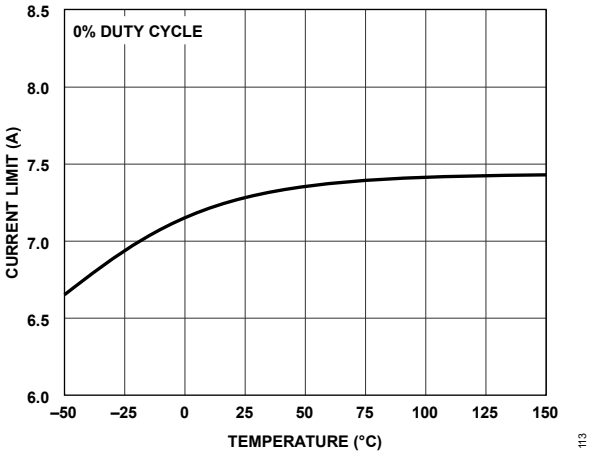


Figure 16. Top FET Current Limit vs. Temperature

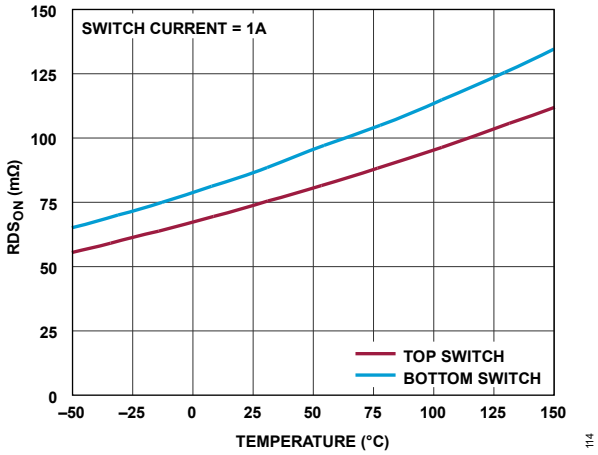


Figure 17. Switch $R_{DS(ON)}$ vs. Temperature

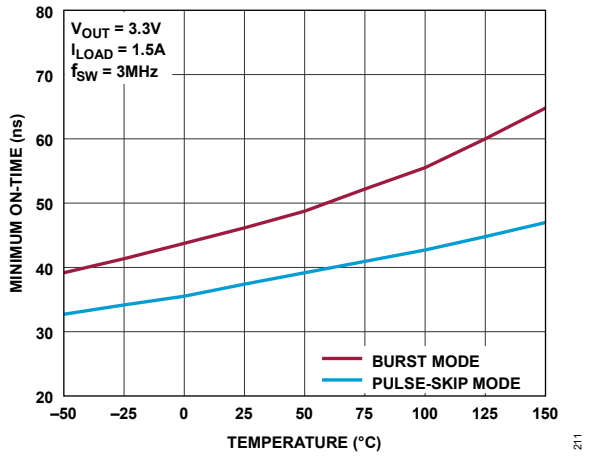


Figure 18. Minimum On-Time vs. Temperature

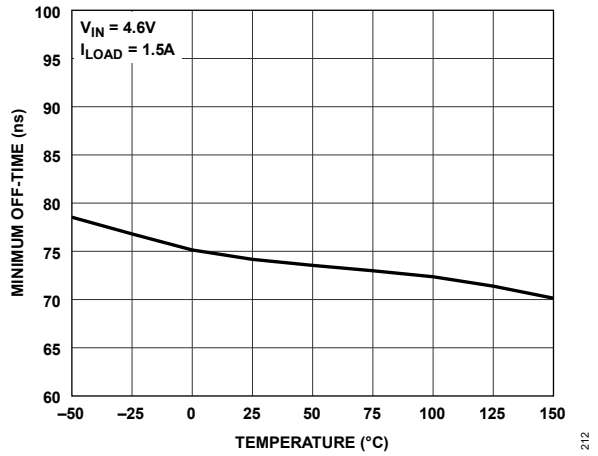


Figure 19. Minimum Off-Time vs. Temperature

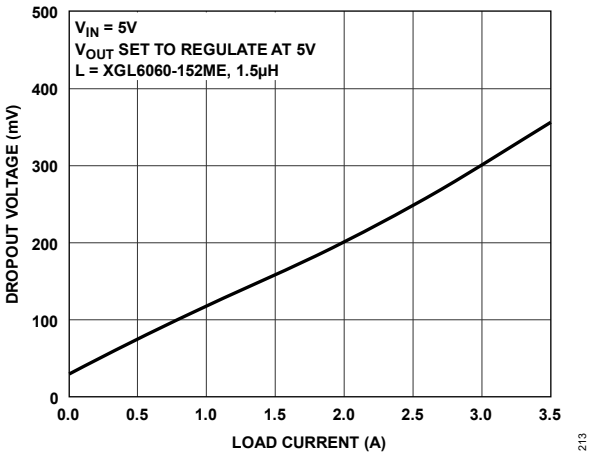


Figure 20. Dropout Voltage vs. Load Current

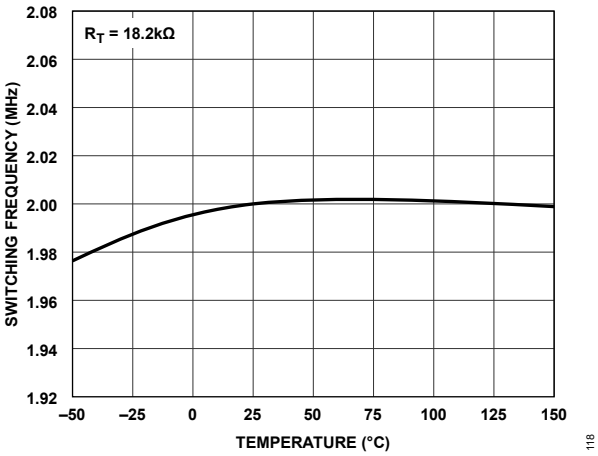


Figure 21. Switching Frequency vs. Temperature

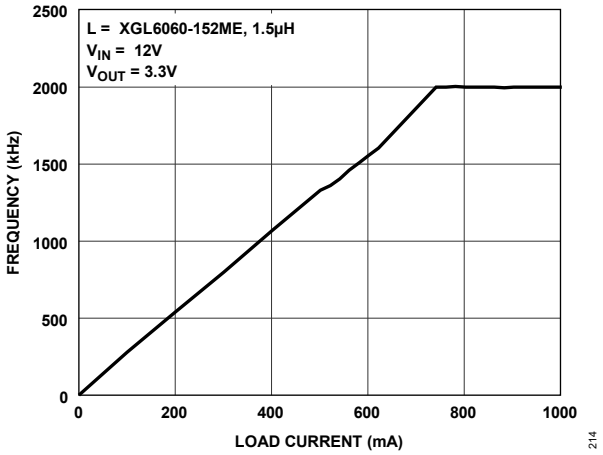


Figure 22. Burst Frequency vs. Load Current

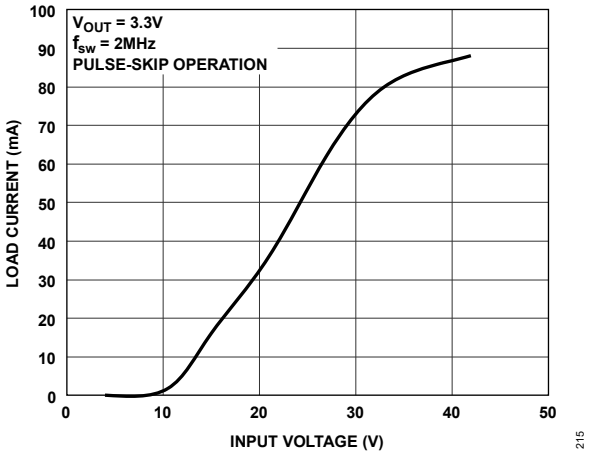


Figure 23. Minimum Load to Full Frequency (Pulse-Skip Mode)

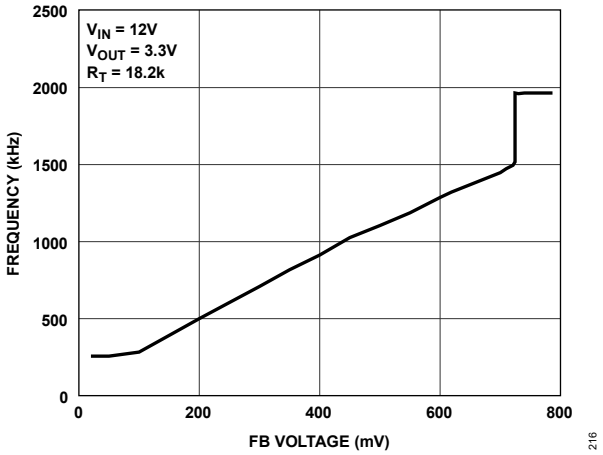


Figure 24. Frequency Foldback

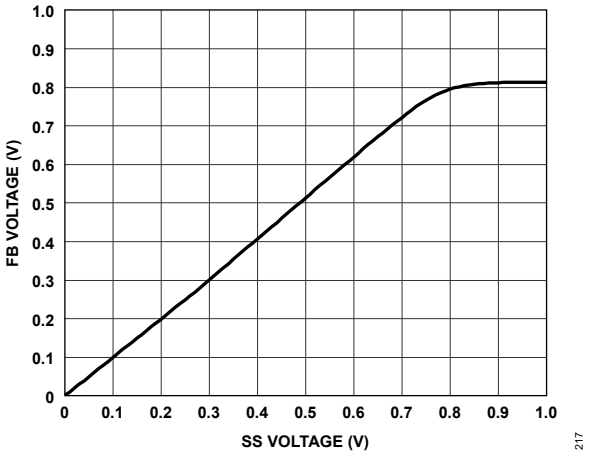


Figure 25. Soft-Start Tracking

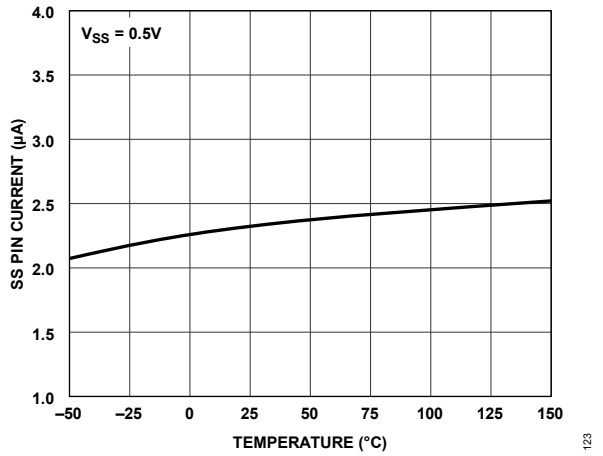


Figure 26. Soft-Start Current vs. Temperature

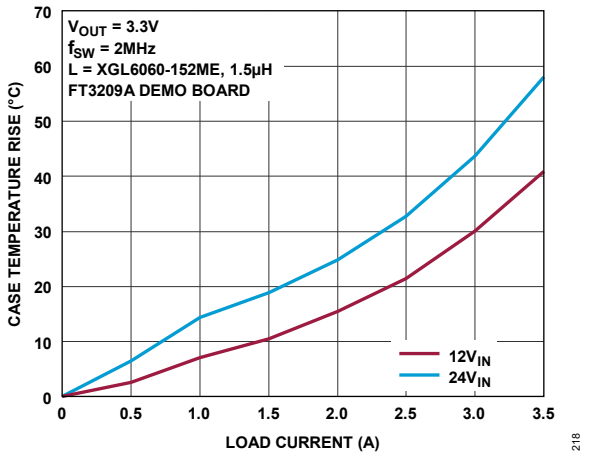
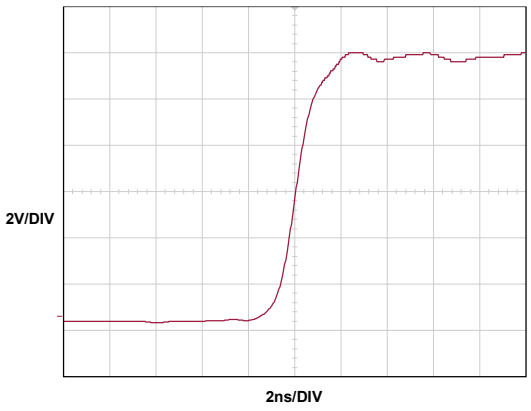


Figure 27. Case Temperature vs. Load Current



V_{IN} = 12V
I_{LOAD} = 2A

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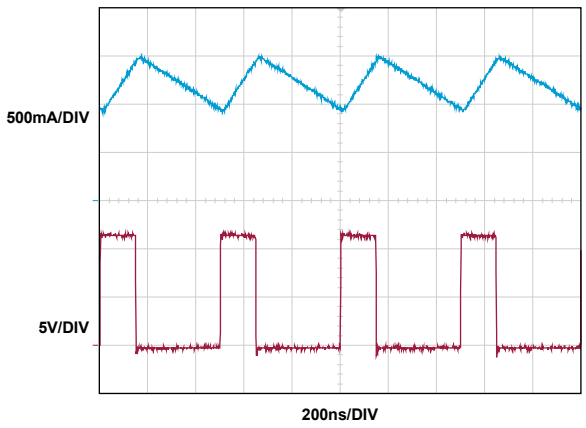
Figure 28. Switching Rising Edge



$12V_{IN}$ TO $3.3V_{OUT}$ AT 1.5A

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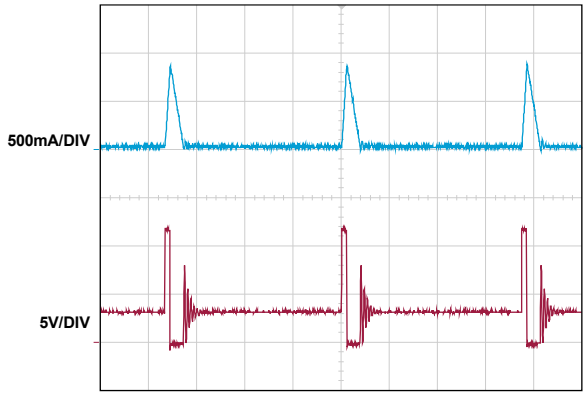
Figure 29. Switching Waveforms



$12V_{IN}$ TO $3.3V_{OUT}$ AT 50mA
BURST MODE OPERATION

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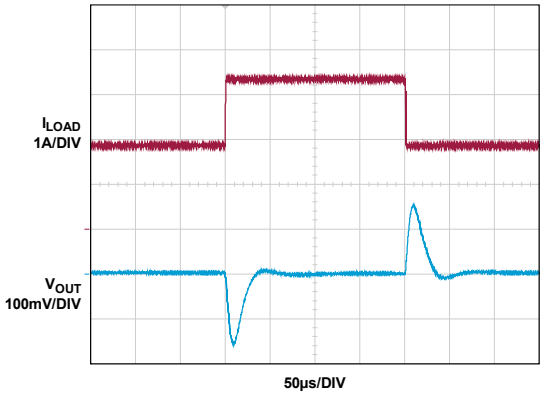
Figure 30. Switching Waveforms



1.85A TO 3.35A TRANSIENT (1.5A PULSE)
$12V_{IN}$ TO $3.3V_{OUT}$
C_{OUT} = 3 x 22µF

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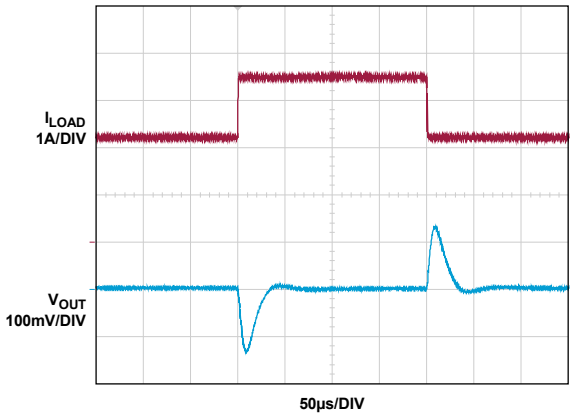
Figure 31. Transient Response



2.2A TO 3.5A TRANSIENT (1.3A PULSE)
$12V_{IN}$ TO $3.3V_{OUT}$
C_{OUT} = 3 x 22µF

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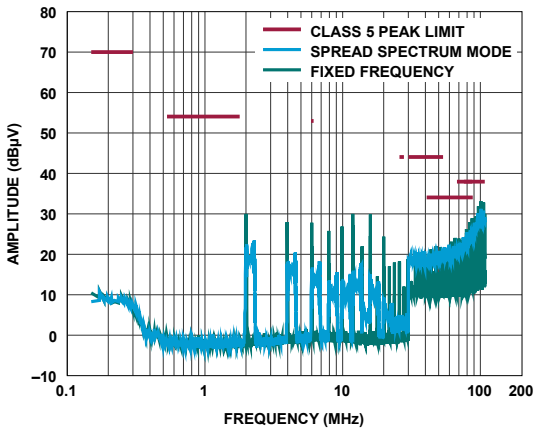
Figure 32. Transient Response



EVAL-LT8615-AZ DEMO BOARD
(WITH EMI FILTER INSTALLED)
12V INPUT TO 5V OUTPUT AT 2.5A, f_{SW} = 2MHz

226

Figure 33. Conducted EMI Performance

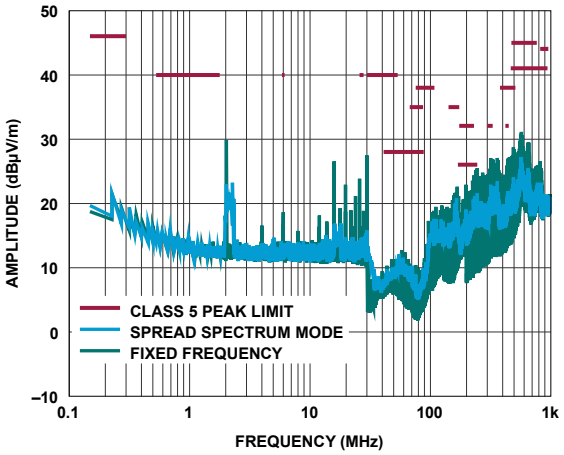


Figure 34. Radiated EMI Performance

BLOCK DIAGRAM

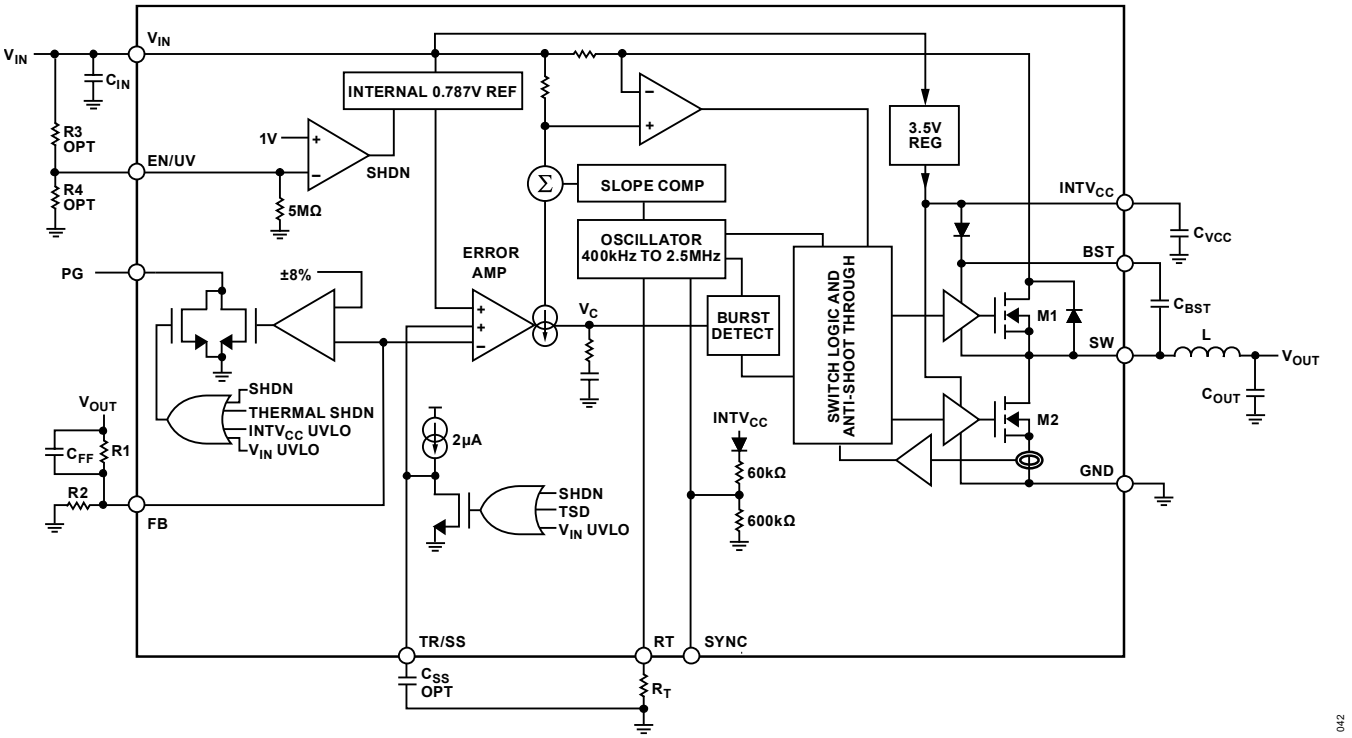


Figure 35. Block Diagram

THEORY OF OPERATION

The LT8615 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 VC node. The error amplifier servos the VC node by comparing the FB pin voltage with an internal 0.787V 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 VC 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 the inductor current falls to zero. If overload conditions result in excess current flowing through the bottom switch, the next clock cycle is delayed until switch current returns to a safe level.

If the EN/UV pin is low, the LT8615 is shut down and draws 1µA from the input. When the EN/UV pin is above 1V, the switching regulator becomes active.

To optimize efficiency at light loads, the LT8615 enters Burst Mode operation during light load situations. Between bursts, all circuitry associated with controlling the output switch is shut down, reducing the input supply current to 1.7µA. In a typical application, 2.5µA is consumed from the input supply when regulating with no load. The SYNC pin is tied low to use Burst Mode operation and can be floated to use pulse-skipping mode. If a clock is applied to the SYNC pin, the part synchronizes to an external clock frequency and operates in pulse-skipping mode. While in pulse-skipping mode, the oscillator operates continuously, and positive SW transitions are aligned to the clock. During light loads, switch pulses are skipped to regulate the output, and the quiescent current is several mA. The SYNC pin may be tied high for spread-spectrum modulation mode, and the LT8615 operates like pulse-skipping mode but varies the clock frequency to reduce EMI.

Comparators on the LT8615 monitoring the FB pin voltage 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.

The oscillator reduces the LT8615's operating frequency when the voltage at the FB pin is low, and the SYNC is setting the part to Burst Mode. This frequency foldback helps to control the inductor current when the output voltage is lower than the programmed value, which occurs during start-up. When a clock is applied to the SYNC pin, the SYNC pin is floated, or held DC high, the LT8615 stays at the programmed frequency without foldback, and only slows switching if the inductor current exceeds safe levels.

APPLICATIONS INFORMATION

Achieving Ultralow Quiescent Current

To enhance efficiency at light loads, the LT8615 enters 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 LT8615 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 LT8615 consumes 1.7µA.

As the output load decreases, the frequency of single current pulses decreases (see *Figure 36*) and the percentage of time the LT8615 is in sleep mode increases, resulting in much higher light load efficiency than for typical converters. By maximizing the time between pulses, the converter 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.

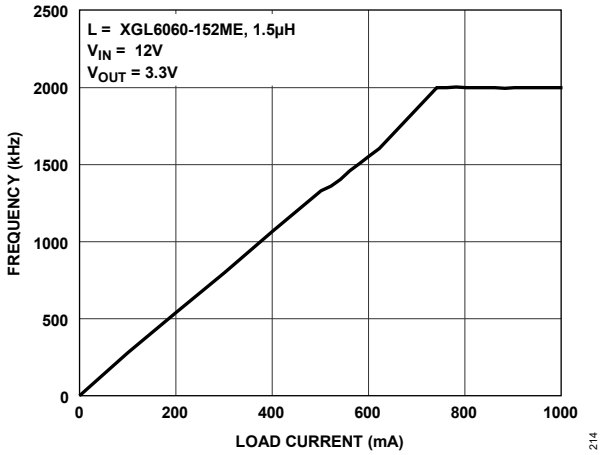


Figure 36. SW Burst Mode Frequency vs. Load

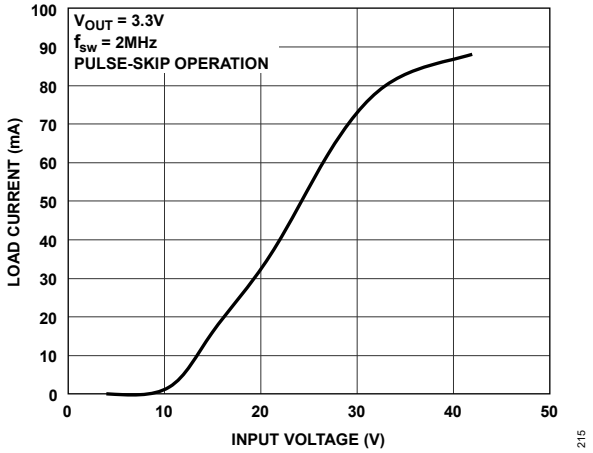


Figure 37. Full Switching Frequency Minimum Load vs. V_{IN} in Pulse-Skipping Mode

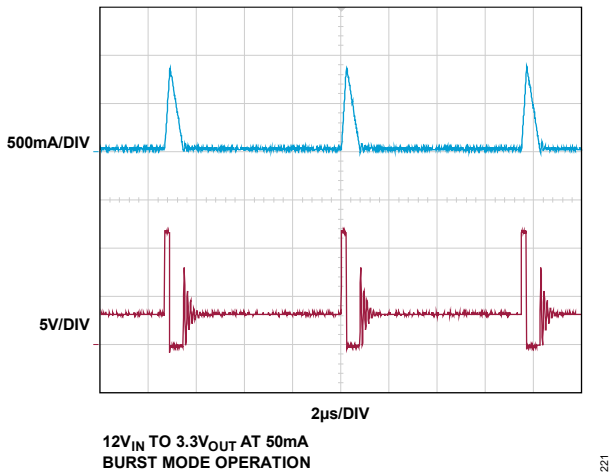


Figure 38. Burst Mode Operation

While in Burst Mode operation, the current limit of the top switch is approximately 1A, resulting in the output voltage ripple shown in *Figure 38*. Increasing the output capacitance decreases the output ripple proportionally. As load ramps upward from zero, the switching frequency increases, but only up to the switching frequency programmed by the resistor at the RT pin, as shown in *Table 4*. The output load at which the LT8615 reaches the programmed frequency varies based on input voltage, output voltage, and inductor choice.

For some applications, it is desirable for the LT8615 to operate in pulse-skipping mode. Pulse-skipping mode offers two major differences from Burst Mode operation. First, the clock stays awake always and all switching cycles are aligned to the clock. In this mode, much of the internal circuitry is awake always, increasing quiescent current to several hundred µA. Second, full switching frequency is reached at lower output load than in Burst Mode operation, as shown in *Figure 37*. To enable pulse-skipping mode, the SYNC pin is floated. To achieve spread-spectrum modulation with pulse-skipping mode, the SYNC pin is tied high. While a clock is applied to the SYNC pin, the LT8615 also operates in pulse-skipping mode.

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 following equation.

$$R1 = R2 \times \left(\frac{V_{OUT}}{0.787V} - 1\right)$$

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

For low input quiescent current and good light-load efficiency, 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 given by the following equation.

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

where, 1.7µA is the quiescent current of the LT8615 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 5V application with R1 = 1M and R2 = 187k, the feedback divider draws 4.2µA. With V_{IN} = 12V and n = 85%, this adds 2µA to the 1.7µA quiescent current,

resulting in 3.7µA no-load current from the 12V supply. Note that the IQ equation implies that the no-load current is a function of V_{IN}; this is plotted in the *Achieving Ultralow Quiescent Current* section.

When using large FB resistors, connect a 4.7pF to 22pF phase-lead capacitor from V_{OUT} to FB.

Setting the Switching Frequency

The LT8615 uses a constant frequency PWM architecture that can be programmed to switch from 400kHz to 2.5MHz by using a resistor tied from the RT pin to ground. *Table 4* shows the necessary R_T value for a desired switching frequency. When in spread-spectrum modulation mode, the frequency is modulated upwards of the frequency set by R_T.

Table 4. Switching Frequency vs R_T Value

f_{SW} (MHz)	R_T (kΩ)
0.4	105
0.5	76.8
0.6	68.1
0.8	51.1
1.0	40.2
1.2	33.2
1.4	27.4
1.6	23.7
1.8	20.5
2.0	18.2
2.2	16.2
2.5	13.7

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:

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

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 (~0.28V, ~0.28V, respectively, at max. load) and $t_{ON(MIN)}$ is the minimum top switch on-time (see *Typical Applications*). This equation shows that 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 Abs Max rating regardless of the R_T value. However, the LT8615 reduces switching frequency as necessary to maintain control of the inductor current to assure safe operation.

The LT8615 is capable of maximum duty cycle approaching 100%, and the V_{IN} to V_{OUT} dropout is limited by the $R_{DS(ON)}$ of the top switch. In this mode, the LT8615 skips switch cycles, resulting in a lower switching frequency than programmed by R_T.

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:

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

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 (~0.28V, ~0.28V, respectively, at max. load), f_{SW} is the switching frequency (set by RT), and $t_{OFF(MIN)}$ is the minimum switch offtime. Note that higher switching frequency increases the minimum input voltage, below which cycles are dropped to achieve higher duty cycle.

Inductor Selection and Maximum Output Current

The LT8615 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 LT8615 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:

$$L = \frac{V_{OUT} + V_{SW(BOT)}}{f_{SW}}$$

where, f_{SW} is the switching frequency in MHz, V_{OUT} is the output voltage, $V_{SW(BOT)}$ is the bottom switch drop (~0.28V), and L is the inductor value in µH.

To avoid overheating and poor efficiency, an inductor must be chosen with an RMS current rating 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:

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

where, ΔI_L is the inductor ripple current as calculated several paragraphs below and $I_{LOAD(MAX)}$ is the maximum output load for a given application.

As a quick example, an application requiring 1A output should use an inductor with an RMS rating of greater than 1A and an I_{SAT} of greater than 1.3A. To keep the efficiency high, the series resistance (DCR) should be less than 0.04Ω, and the core material should be intended for high frequency applications.

The LT8615 limits the peak switch current to protect the switches and the system from overload faults. The top switch current limit (I_{LIM}) is typically 7.3A at low duty cycles and decreases linearly to 6.1A at D = 0.8. 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:

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

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

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

where, f_{SW} is the switching frequency of the LT8615, and L is the value of the inductor. Therefore, the maximum output current the LT8615 delivers depends on minimum 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.

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 LT8615 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, refer to Application Note 44: *LT1074/LT1076 Design Manual.*

For duty cycles greater than 50% (V_{OUT}/V_{IN} > 0.5), a minimum inductance is required to avoid sub-harmonic oscillation. Refer to Application Note 19: *LT1070 Design Manual* for more details.

$$L_{MIN} = \frac{V_{IN} \times (2 \times DC - 1)}{1.5 \times f_{SW}}$$

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

Input Capacitor

Bypass the input of the LT8615 circuit with a ceramic capacitor of X7R or X5R type. Y5V types have poor performance over temperature and applied voltage, and should not be used. A 4.7µF to 10µF ceramic capacitor is adequate to bypass the LT8615 and easily handles the ripple current. 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.

Step-down regulators draw current from the input supply in pulses with very fast rise and fall times. The input capacitor is required to reduce the resulting voltage ripple at the LT8615 and to force this very high frequency switching current into a tight local loop, minimizing the EMI. A 4.7µF capacitor is capable of this task, but only if it is placed close to the LT8615 (see the *PCB Layout* section). A second precaution regarding the ceramic input capacitor concerns the maximum input voltage rating of the LT8615. A ceramic input capacitor combined with trace or cable inductance forms a high quality (under damped) tank circuit. If the LT8615 circuit is plugged into a live supply, the input voltage can ring to twice its nominal value, possibly exceeding the LT8615's voltage rating. This situation is easily avoided (refer to Application Note 88*: Ceramic Input Capacitors Can Cause Overvoltage Transients*).

Output Capacitor and Output Ripple

The output capacitor has two essential functions. Along with the inductor, it filters the square wave generated by the LT8615 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 to satisfy transient loads and stabilize the LT8615's control loop. Ceramic capacitors have very low equivalent series resistance (ESR) and provide the best ripple performance. A good starting value is:

$$C_{OUT} = \frac{100}{V_{OUT} \times f_{SW}}$$

Where, f_{SW} is in MHz, and C_{OUT} is the recommended output capacitance in µF. Use X5R or X7R types. This choice will provide low output ripple and good transient response. Increasing the output capacitance also decreases the output voltage ripple. A capacitor with lower output value can be used to save space and cost but transient performance suffers and may cause loop instability. See the *Typical Applications* in this data sheet for suggested capacitor values.

When choosing a capacitor, pay special attention 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 LT8615 due to their piezoelectric nature. When in Burst Mode operation, the LT8615's switching frequency depends on the load current, and at very light loads, the LT8615 can excite the ceramic capacitor at audio frequencies, generating audible noise. Since the LT8615 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.

A final precaution regarding ceramic capacitors concerns the maximum input voltage rating of the LT8615. As previously mentioned, a ceramic input capacitor combined with trace or cable inductance forms a high quality (under damped) tank circuit. If the LT8615 circuit is plugged into a live supply, the input voltage can ring to twice its nominal value, possibly exceeding the LT8615's rating. This situation is easily avoided (refer to Application Note 88: *Ceramic Input Capacitors Can Cause Overvoltage Transients*).

Enable Pin

The LT8615 is in shutdown when the EN pin is low and active when the pin is high. The rising threshold of the EN comparator is 1.05V, with 50mV 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 LT8615 to regulate the output only when V_{IN} is above a desired voltage (see *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:

$$V_{IN(EN)} = \left(\frac{R3}{R4} + 1\right) \times 1V$$

where, the LT8615 remains off until V_{IN} is above $V_{IN(EN)}$. Due to the comparator's hysteresis, switching does not stop until the input falls slightly below $V_{IN(EN)}$. When 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 LT8615. 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 3.5V supply from V_{IN} that powers the drivers and the internal bias circuitry. The $INTV_{CC}$ can supply enough current for the LT8615's circuitry and must be bypassed to ground with a minimum of 1µF ceramic capacitor. Good bypassing is necessary to supply the high transient currents required by the power MOSFET gate drivers. Applications with high input voltage and high switching frequency increase die temperature because of the higher power dissipation across the LDO. Do not connect an external load to the $INTV_{CC}$ pin.

Output Voltage Tracking and Soft-Start

The LT8615 allows the user to program its output voltage ramp rate with 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 soft-start ramp, the output voltage proportionally tracks the TR/SS pin voltage. For output tracking applications, TR/SS can be externally driven by another voltage source. From 0V to 0.787V, the TR/SS voltage overrides the internal 0.787V reference input to the error amplifier, thus regulating the FB pin voltage to that of the TR/SS pin. When TR/SS is above 0.787V, tracking is disabled, and the feedback voltage regulates to the internal reference voltage.

An active pull-down circuit is connected to the TR/SS pin, which discharges the external soft-start capacitor in the case of fault conditions and restarts 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 LT8615'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 0.5% of hysteresis.

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.

Synchronization

To select low ripple Burst Mode operation, tie the SYNC pin below 0.4V (this can be ground or a logic low output). To synchronize the LT8615 oscillator to an external frequency, connect a square wave to the SYNC pin. The square wave amplitude should have values below 0.4V and peaks above 1.5V (up to 5V). The square wave's duty cycle can be as low as with minimum peaks of 50ns or as high as with minimum valleys of 50ns.

The LT8615 does not enter Burst Mode operation at low output loads while synchronized to an external clock, but instead pulse skips to maintain regulation. The LT8615 may be synchronized over a 400kHz to 2.5MHz range. The R_T resistor should be chosen to set the LT8615 switching frequency equal to or below the lowest synchronization input. For example, if the synchronization signal is 2MHz or higher, the R_T is selected for 2MHz. The slope compensation is set by the R_T 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 does not change the slopes of the inductor current waveform, if the inductor is large enough to avoid subharmonic oscillations at the frequency set by R_T, then the slope compensation is sufficient for all synchronization frequencies.

For some applications, it is desirable for the LT8615 to operate in pulse-skipping mode. Pulse-skipping mode offers two major differences from Burst Mode operation. First, the clock stays awake always and all switching cycles are

aligned to the clock. Second, full switching frequency is reached at lower output load than in Burst Mode operation, as shown in *Figure 37*. These two differences come at the expense of increased quiescent current. To enable pulse-skipping mode, the SYNC pin is floated.

For some applications, reduced EMI operation may be desirable, which can be achieved through spread-spectrum modulation. This mode operates like the pulse-skipping mode operation, with the key difference that the switching frequency is modulated up and down by a 3kHz triangle wave. The modulation has the frequency set by RT as the low frequency, and modulates up to approximately 20% higher than the frequency set by RT. To enable spread-spectrum mode, tie SYNC to $INTV_{CC}$ or drive to a voltage between 3.2V and 5V.

The LT8615 does not operate in forced continuous mode regardless of SYNC signal.

Shorted and Reversed Input Protection

The LT8615 tolerates a shorted output. Several features are used for protection during output short-circuit and brownout conditions. The first is the switching frequency, which is folded back while the output is lower than the set point to maintain inductor current control. Second, the bottom switch current is monitored such that if the inductor current is beyond safe levels, switching of the top switch is delayed until the inductor current falls to safe levels. This allows for tailoring the LT8615 to individual applications and limiting thermal dissipation during short-circuit conditions.

Frequency foldback behavior depends on the state of the SYNC pin. If the SYNC pin is low, the switching frequency slows while the output voltage is lower than the programmed level. If the SYNC pin is connected to a clock source, floated, or tied high, the LT8615 stays at the programmed frequency without foldback and only slow switching if the inductor current exceeds safe levels.

There is another situation to consider in systems where the output is held high when the input to the LT8615 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 LT8615'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 LT8615's internal circuitry pulls its quiescent current through its SW pin. This is acceptable if the system can tolerate several µA in this state. If the EN pin is grounded, the SW pin current drops to near 0.7µA. However, if the V_{IN} pin is grounded while the output is held high, regardless of EN, parasitic body diodes inside the LT8615 can pull current from the output through the SW pin and the V_{IN} pin. *Figure 39* shows a connection of the V_{IN} and EN/UV pins that allow the LT8615 to run only when the input voltage is present and that protects against a shorted or reversed input.

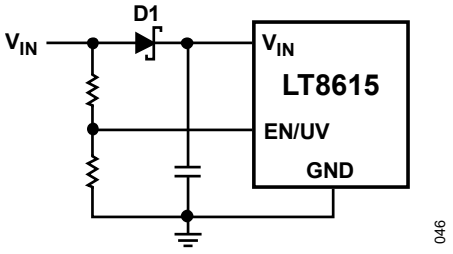


Figure 39. Reverse V_{IN} Protection

PCB Layout

For proper operation and minimum EMI, care must be taken during printed circuit board (PCB) layout. *Figure 40* shows the recommended component placement with trace, ground plane, and via locations. Note that large, switched currents flow in the LT8615's V_{IN} pins, GND pins, and the input capacitor (C_{IN}). The loop formed by the input

capacitor should be as small as possible by placing the capacitor adjacent to the V_{IN} and GND pins. When using a physically large input capacitor, the resulting loop may become too large. In this case, using a small case/value capacitor placed close to the V_{IN} and GND pins plus a larger capacitor further away is preferred. These components, along with the inductor and output capacitor, 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 RT node small so that the ground traces shield them from the SW and BOOST nodes. The exposed pad on the bottom of the package must be soldered to ground so that the pad is connected to ground electrically and also acts as a heat sink. To keep thermal resistance low, extend the ground plane as much as possible, and add thermal vias under and near the LT8615 to additional ground planes within the circuit board and on the bottom side.

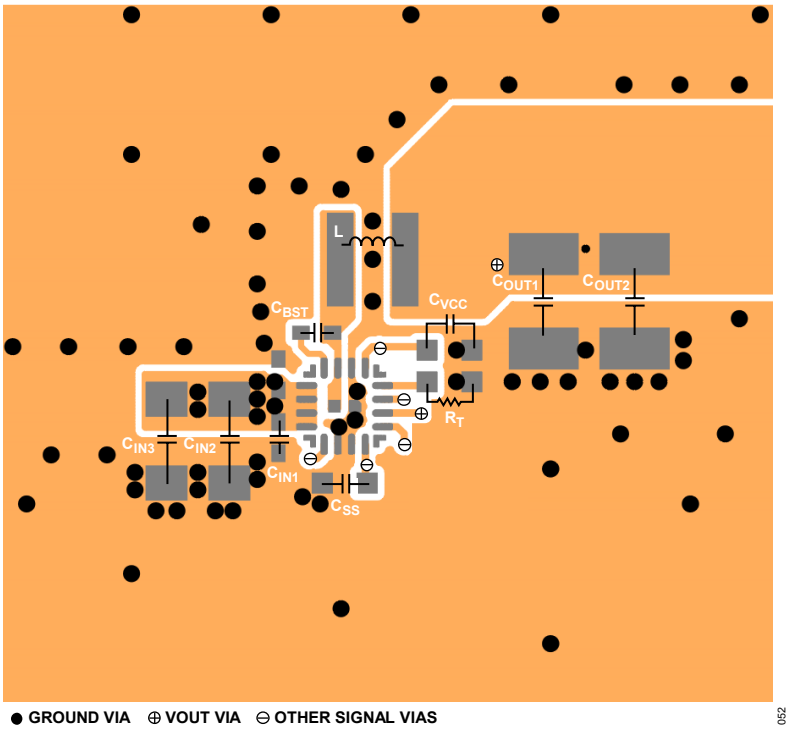


Figure 40. PCB Layout

Thermal Considerations and Peak Current Output

For higher ambient temperatures, care should be taken in the layout of the PCB to ensure good heat sinking of the LT8615. The exposed pad at the bottom of the package must be soldered to a ground plane. This ground should be tied to large copper layers below with thermal vias; these layers spread the heat dissipated by the LT8615. 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 LT8615 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 LT8615 power dissipation by the thermal resistance from junction to ambient. The LT8615 stops switching and indicates a fault condition if the safe junction temperature is exceeded.

Temperature rise of the LT8615 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 41* shows how case temperature rise can be managed by reducing V_{IN}.

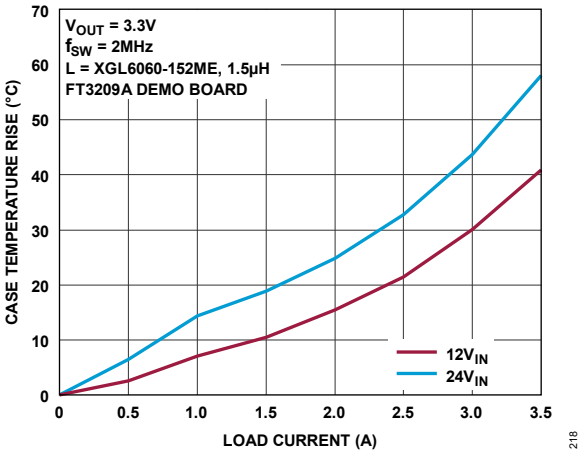


Figure 41. Case Temperature Rise vs. Load Current

TYPICAL APPLICATIONS

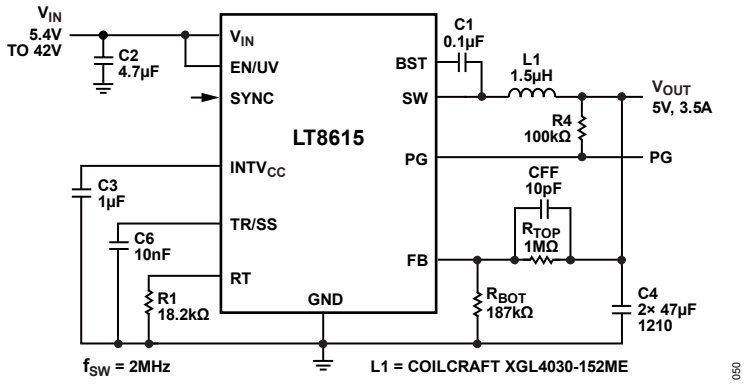


Figure 42. 5V Step-Down Converter

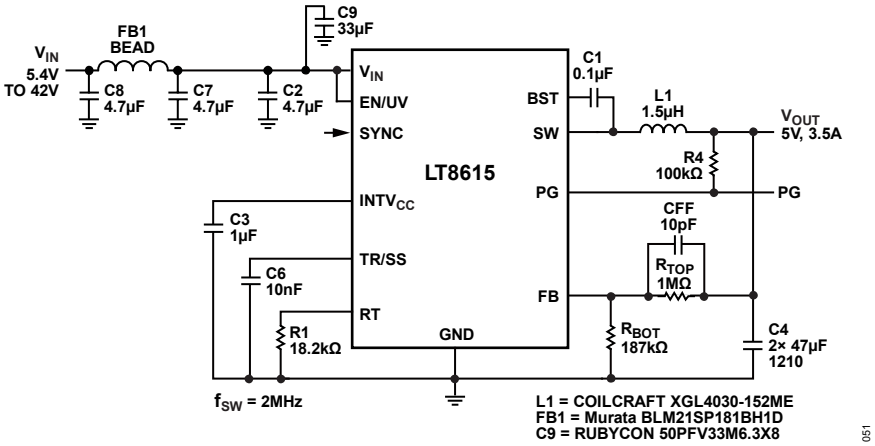


Figure 43. Ultralow EMI 5V Step-Down Converter

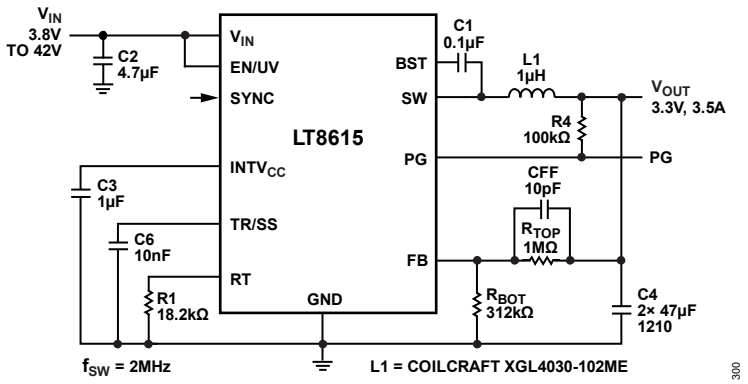


Figure 44. 3.3V Step-Down Converter

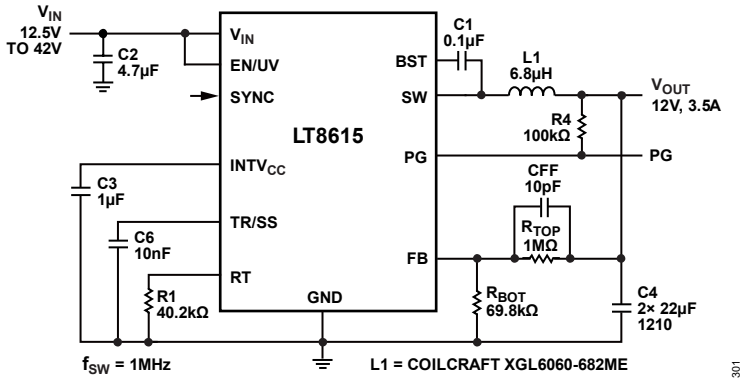


Figure 45. 12V Step-Down Converter

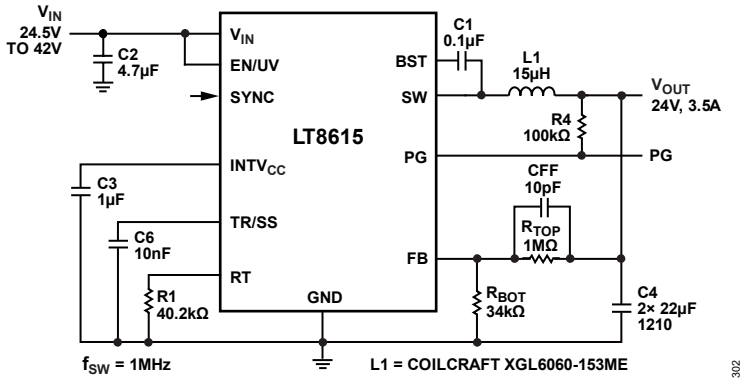
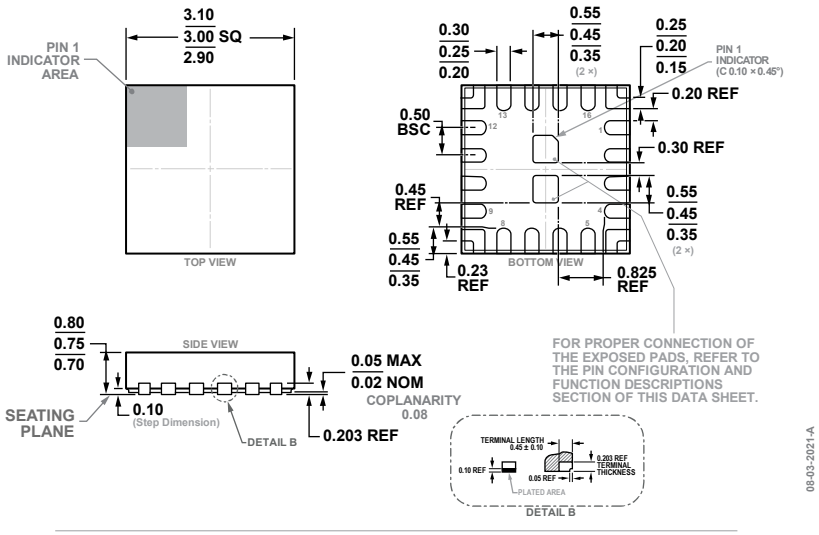


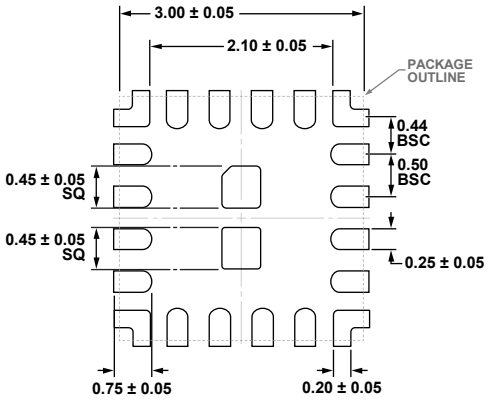
Figure 46. 24V Step-Down Converter

OUTLINE DIMENSIONS

Refer to *https://www.analog.com/en/design-center/packaging-quality-symbols-footprints.html* for the most recent package drawings.



RECOMMENDED SOLDER PAD LAYOUT
APPLY SOLDER MASK TO AREAS THAT ARE NOT SOLDERED



16-Lead Lead Frame Chip Scale Package [LFCSP_SS]
3 x 3 mm Body, With Side Solderable Leads
(CS-16-2)
Dimensions shown in millimeters

ORDERING GUIDE

Table 5. Ordering Guide

LEAD FREE FINISH	TAPE AND REEL	PART MARKING	PACKAGE DESCRIPTION	TEMPERATURE RANGE
LT8615RUDM#PBF	LT8615RUDM#TRPBF	LHWC	16-Lead (3mm × 3mm) Plastic QFN	–40°C to +150°C
AUTOMOTIVE PRODUCTS**				
LT8615RUDM#WPBF	LT8615RUDM#WTRPBF	LHWC	16-Lead (3mm × 3mm) Plastic QFN	–40°C to +150°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.

**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.

RELATED PARTS

PART NUMBER	DESCRIPTION	COMMENTS
LT8608/ LT8608B	42V, 1.5A Synchronous Step-Down Regulator with 2.5µA Quiescent Current	$V_{IN(MIN)}$ = 3.2V, $V_{IN(MAX)}$ = 42V, $V_{OUT(MIN)}$ = 0.778V, I_Q= 2.5µA, I_{SD} = 1µA, MSOP-10E, 2mm × 2mm DFN-8
LT8609/ LT8609A	42V, 3A, 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, 3mm x 3mm DFN-10
LT8640A	42V, 5A/8A Peak Synchronous Step-Down Silent Switcher with 2.5µA Quiescent Current	V_{IN} = 3.4V to 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, 3mm × 4mm QFN-18 Package
LT8614	42V, 4A Synchronous Step-Down Silent Switcher with 2.5µA Quiescent Current	V_{IN} = 3.4V to 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} = 1µA, 3mm × 4mm QFN-18 Package
LT8610A/ LT8610AB	42V, 3.5A, 96% Efficiency, 2.2MHz Synchronous MicroPower Step-Down DC/DC Converter with I_Q = 2.5µA	V_{IN} = 3.4V to 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, MSOP-16E Package
LT8610AC	42V, 3.5A, 96% Efficiency, 2.2MHz Synchronous MicroPower Step-Down DC/DC Converter with I_Q = 2.5µA	V_{IN} = 3V to 42V, $V_{OUT(MIN)}$ = 0.8V, I_Q = 2.5µA, I_{SD} < 1µA, MSOP-16E Package
LT8611	42V, 2.5A, 96% Efficiency, 2.2MHz Synchronous MicroPower Step-Down DC/DC Converter with I_Q = 2.5µA and Input/Output Current Limit/Monitor	V_{IN} = 3.4V to 42V, $V_{OUT(MIN)}$ = 0.97V, I_Q = 2.5µA, I_{SD} < 1µA, 3mm × 5mm QFN-24 Package