

3A, 4MHz, Monolithic Synchronous Step-Down Regulator

FEATURES

- **High Efficiency: Up to 95%**
- **3A Output Current**
- **Low Quiescent Current: 64μA**
- **Low $R_{DS(ON)}$ Internal Switch: 77mΩ**
- **2.25V to 5.5V Input Voltage Range**
- **Programmable Frequency: 300kHz to 4MHz**
- **±2% Output Voltage Accuracy**
- **0.8V Reference Allows Low Output Voltage**
- **Selectable Forced Continuous/Burst Mode® Operation with Adjustable Burst Clamp**
- **Synchronizable Switching Frequency**
- **Low Dropout Operation: 100% Duty Cycle**
- **Power Good Output Voltage Monitor**
- **Overtemperature Protected**
- **Available in 16-Lead Exposed Pad TSSOP and QFN Packages**

APPLICATIONS

- Point-of-Load Regulation
- Notebook Computers
- Portable Instruments
- Distributed Power Systems

DESCRIPTION

The LTC®3412A is a high efficiency monolithic synchronous, step-down DC/DC converter utilizing a constant frequency, current mode architecture. It operates from an input voltage range of 2.25V to 5.5V and provides a regulated output voltage from 0.8V to 5V while delivering up to 3A of output current. The internal synchronous power switch with 77mΩ on-resistance increases efficiency and eliminates the need for an external Schottky diode. Switching frequency is set by an external resistor or can be synchronized to an external clock. 100% duty cycle provides low dropout operation extending battery life in portable systems. OPTI-LOOP® compensation allows the transient response to be optimized over a wide range of loads and output capacitors.

The LTC3412A can be configured for either Burst Mode operation or forced continuous operation. Forced continuous operation reduces noise and RF interference while Burst Mode operation provides high efficiency by reducing gate charge losses at light loads. In Burst Mode operation, external control of the burst clamp level allows the output voltage ripple to be adjusted according to the application requirements.

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TYPICAL APPLICATION

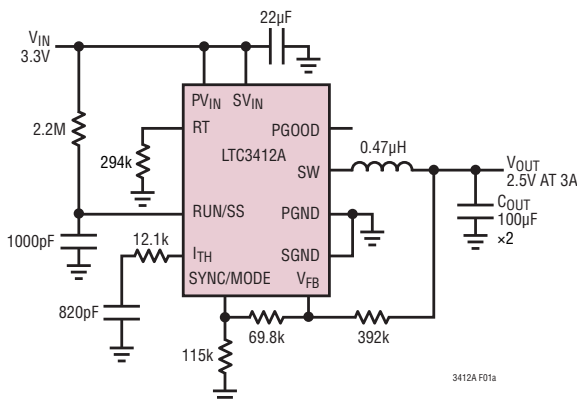
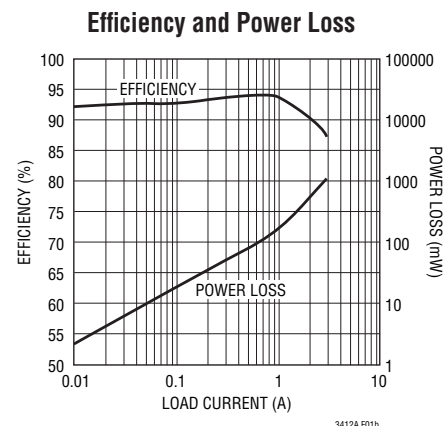


Figure 1. 2.5V/3A Step-Down Regulator



LTC3412A

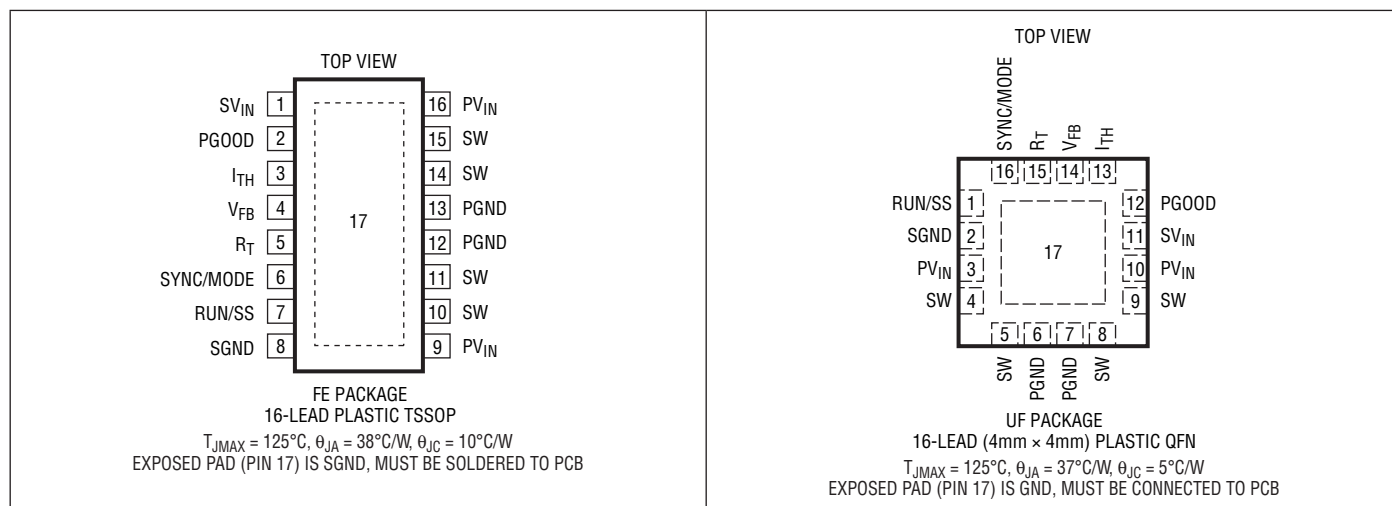
ABSOLUTE MAXIMUM RATINGS

(Note 1)

Input Supply Voltage -0.3V to 6V
 I_{TH} , RUN/SS, V_{FB} , PGOOD,
 SYNC/MODE Voltages -0.3 to V_{IN}
 SW Voltages -0.3V to ($V_{IN} + 0.3V$)

Operating Junction Temperature Range (Notes 2, 5)
 E-, I-Grades -40°C to 125°C
 MP-Grade -55°C to 125°C
 Junction Temperature (Note 5) 125°C
 Lead Temperature (Soldering, 10 sec) 300°C

PIN CONFIGURATION



ORDER INFORMATION

LEAD FREE FINISH	TAPE AND REEL	PART MARKING*	PACKAGE DESCRIPTION	TEMPERATURE RANGE
LTC3412AEFE#PBF	LTC3412AEFE#TRPBF	3412AEFE	16-Lead Plastic TSSOP	-40°C to 125°C
LTC3412AIFE#PBF	LTC3412AIFE#TRPBF	3412AIFE	16-Lead Plastic TSSOP	-40°C to 125°C
LTC3412AEUF#PBF	LTC3412AEUF#TRPBF	3412A	16-Lead (4mm x 4mm) Plastic QFN	-40°C to 125°C
LTC3412AIUF#PBF	LTC3412AIUF#TRPBF	3412A	16-Lead (4mm x 4mm) Plastic QFN	-40°C to 125°C
LEAD BASED FINISH	TAPE AND REEL	PART MARKING*	PACKAGE DESCRIPTION	TEMPERATURE RANGE
LTC3412AEFE	LTC3412AEFE#TR	3412AEFE	16-Lead Plastic TSSOP	-40°C to 125°C
LTC3412AIFE	LTC3412AIFE#TR	3412AIFE	16-Lead Plastic TSSOP	-40°C to 125°C
LTC3412AMPFE	LTC3412AMPFE#TR	3412AMPFE	16-Lead Plastic TSSOP	-55°C to 125°C
LTC3412AEUF	LTC3412AEUF#TR	3412A	16-Lead (4mm x 4mm) Plastic QFN	-40°C to 125°C
LTC3412AIUF	LTC3412AIUF#TR	3412A	16-Lead (4mm x 4mm) Plastic QFN	-40°C to 125°C

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

For more information on lead free part marking, go to: <http://www.linear.com/leadfree/>

For more information on tape and reel specifications, go to: <http://www.linear.com/tapeandreeel/>

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating junction temperature range, otherwise specifications are at $T_A \approx T_J = 25^\circ\text{C}$. $V_{IN} = 3.3\text{V}$ unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
SV _{IN}	Signal Input Voltage Range			2.25		5.5	V
V _{FB}	Regulated Feedback Voltage	(Note 3) E-, I-Grades MP-Grade	● ●	0.784 0.780	0.800 0.800	0.816 0.816	V V
I _{FB}	Voltage Feedback Leakage Current				0.1	0.2	μA
ΔV _{FB}	Reference Voltage Line Regulation	V _{IN} = 2.7V to 5.5V (Note 3)	●		0.04	0.2	%V
V _{LOADREG}	Output Voltage Load Regulation	Measured in Servo Loop, V _{ITH} = 0.36V Measured in Servo Loop, V _{ITH} = 0.84V	● ●		0.02 −0.02	0.2 −0.2	% %
ΔV _{PGOOD}	Power Good Range				±7.5	±9	%
R _{PGOOD}	Power Good Pull-Down Resistance				120	200	Ω
I _Q	Input DC Bias Current Active Current Sleep Shutdown	(Note 4) V _{FB} = 0.78V, V _{ITH} = 1V V _{FB} = 1V, V _{ITH} = 0V V _{RUN} = 0V, V _{MODE} = 0V			250 64 0.02	330 80 1	μA μA μA
f _{OSC}	Switching Frequency Switching Frequency Range	R _{OSC} = 294kΩ (Note 6)		0.88 0.3	1	1.1 4	MHz MHz
f _{SYNC}	SYNC Capture Range	(Note 6)		0.3		4	MHz
R _{PFET}	R _{DS(ON)} of P-Channel FET	I _{SW} = 1A (Note 7)			77	110	mΩ
R _{NFET}	R _{DS(ON)} of N-Channel FET	I _{SW} = −1A (Note 7)			65	90	mΩ
I _{LIMIT}	Peak Current Limit			4.5	6		A
V _{UVLO}	Undervoltage Lockout Threshold			1.75	2	2.25	V
I _{LSW}	SW Leakage Current	V _{RUN} = 0V, V _{IN} = 5.5V			0.1	1	μA
V _{RUN}	RUN Threshold			0.5	0.65	0.8	V
I _{RUN}	RUN/SS Leakage Current					1	μA

Note 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.

Note 2: The LTC3412AE is guaranteed to meet performance specifications from 0°C to 85°C . Specifications over the -40°C to 125°C operating junction temperature range are assured by design, characterization and correlation with statistical process controls. The LTC3412AI is guaranteed to meet performance specifications over the -40°C to 125°C operating junction temperature range. The LTC3412AMP is guaranteed and tested to meet performance specifications over the full -55°C to 125°C operating junction temperature range. Note that the maximum ambient temperature consistent with these specifications is determined by specific operating conditions in conjunction with board layout, the rated package thermal resistance and other environmental factors.

Note 3: The LTC3412A is tested in a feedback loop that adjusts V_{FB} to achieve a specified error amplifier output voltage (I_{TH}).

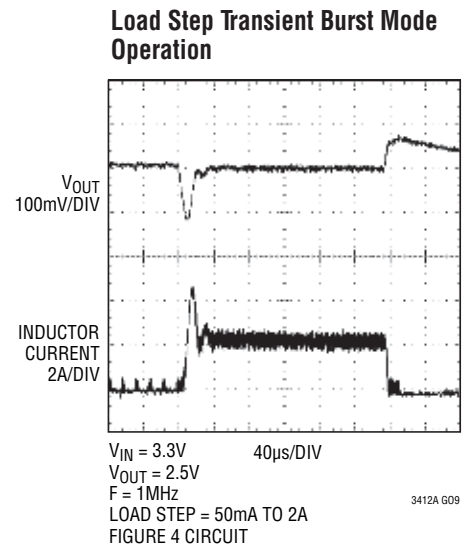
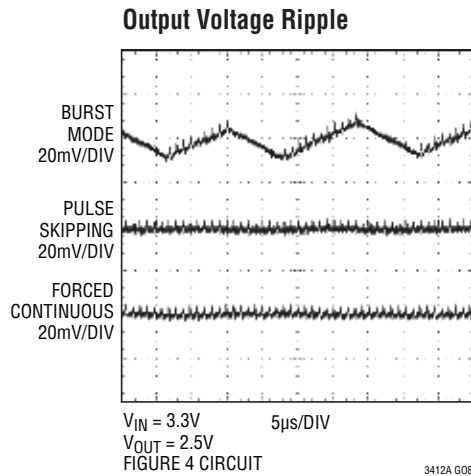
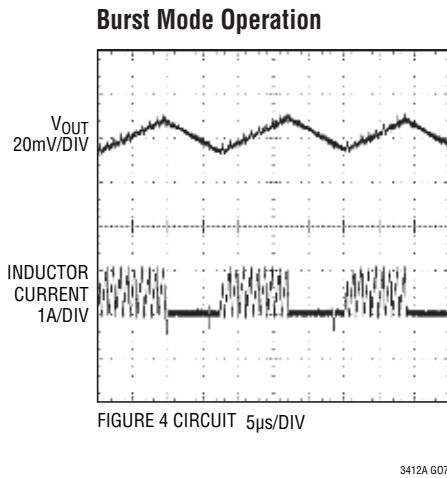
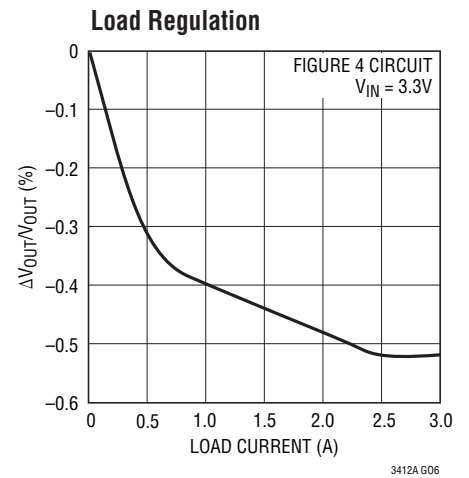
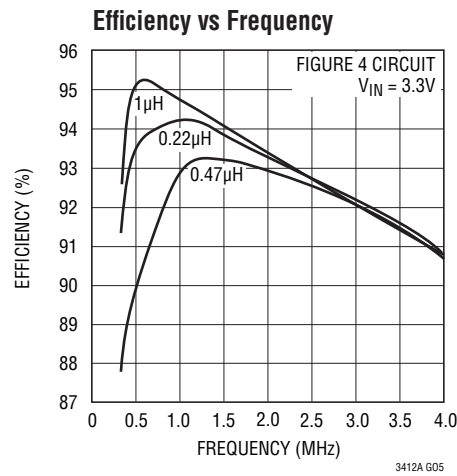
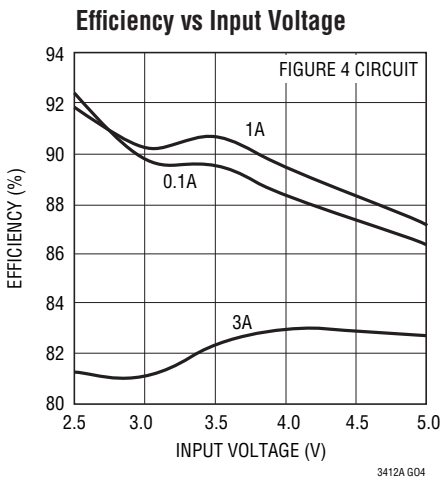
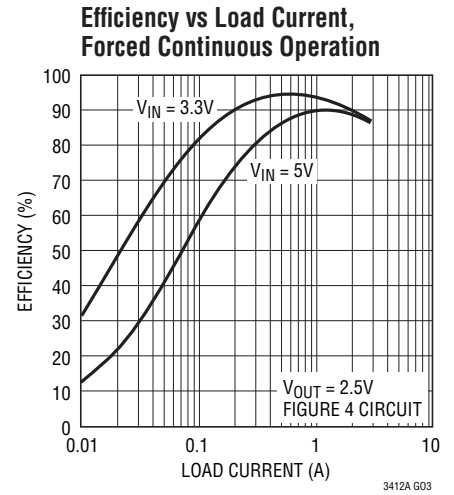
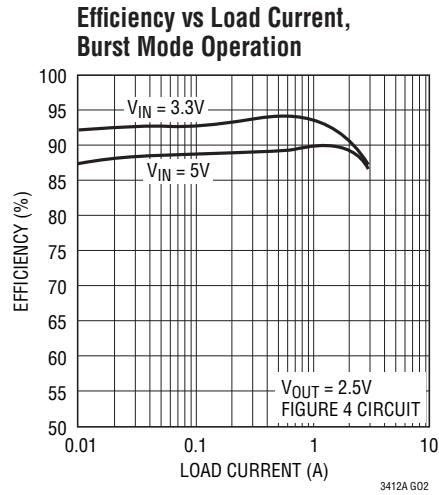
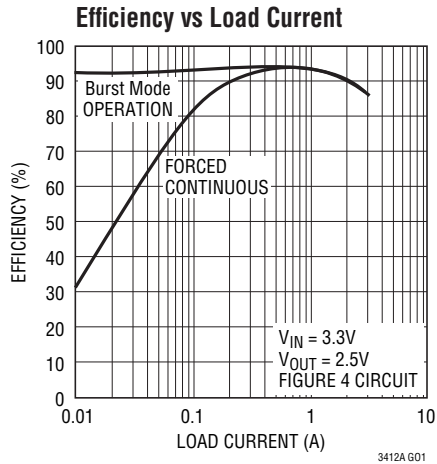
Note 4: Dynamic supply current is higher due to the internal gate charge being delivered at the switching frequency.

Note 5: T_J is calculated from the ambient temperature T_A and power dissipation as follows: LTC3412AFE: $T_J = T_A + P_D$ ($38^\circ\text{C}/\text{W}$)
LTC3412AUF: $T_J = T_A + P_D$ ($34^\circ\text{C}/\text{W}$)

Note 6: 4MHz operation is guaranteed by design and not production tested.

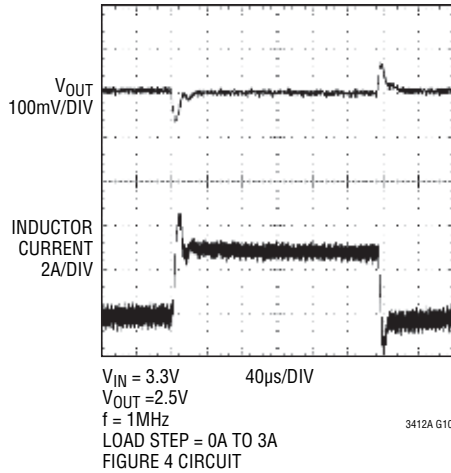
Note 7: Switch on resistance is guaranteed by design and test condition in the UF package and by final test correlation in the FE package.

TYPICAL PERFORMANCE CHARACTERISTICS

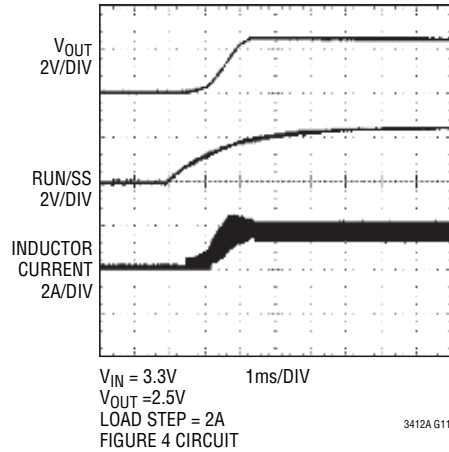


TYPICAL PERFORMANCE CHARACTERISTICS

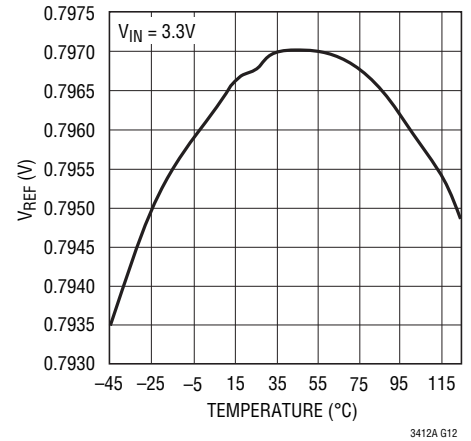
Load Step Transient Forced Continuous



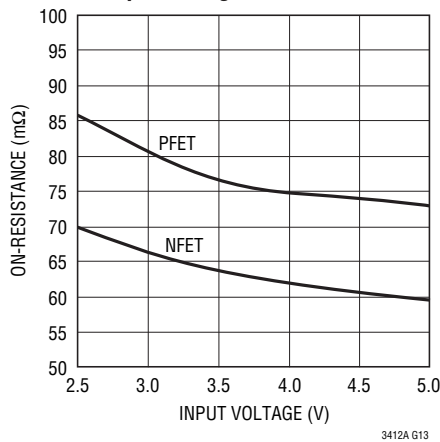
Start-Up Transient



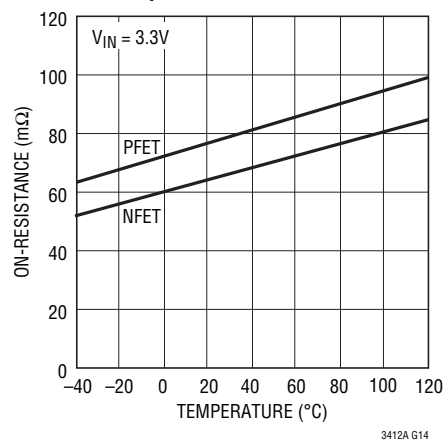
V_{REF} vs Temperature



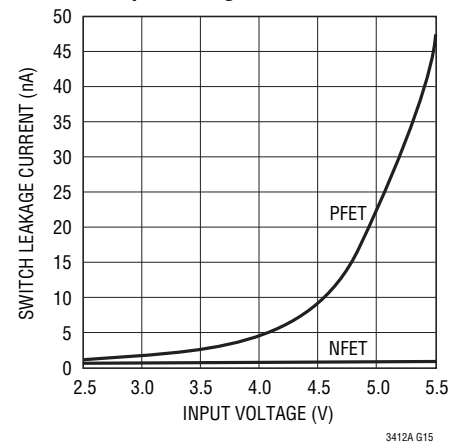
Switch On-Resistance vs Input Voltage



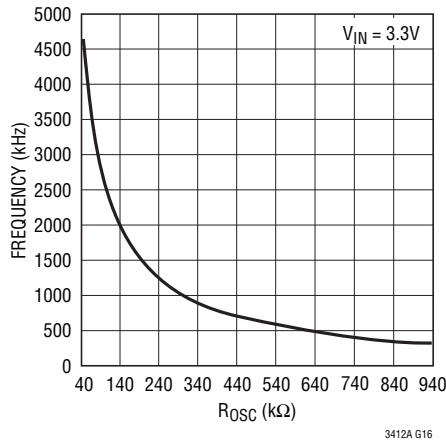
Switch On-Resistance vs Temperature



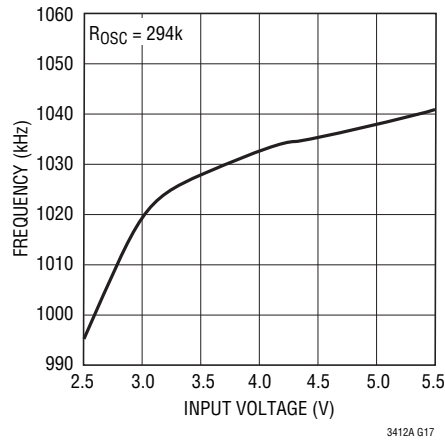
Switch Leakage Current vs Input Voltage



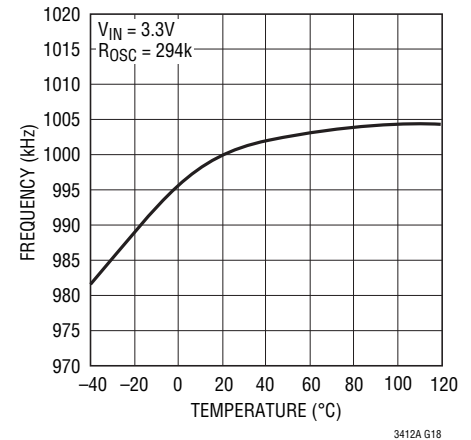
Frequency vs R_{OSC}



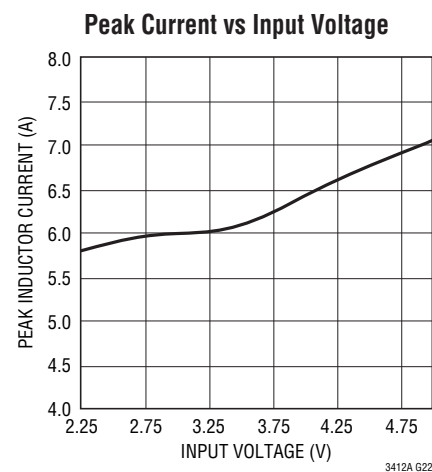
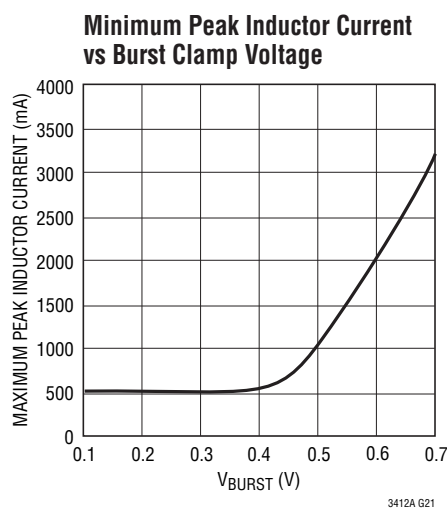
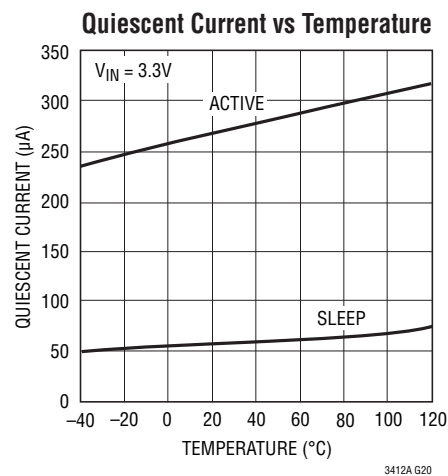
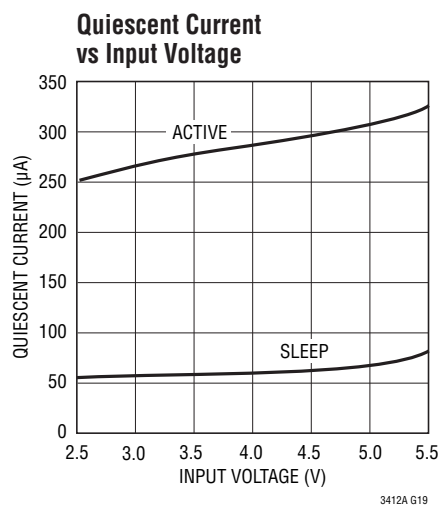
Frequency vs Input Voltage



Frequency vs Temperature



TYPICAL PERFORMANCE CHARACTERISTICS



PIN FUNCTIONS (FE/UHF)

SV_{IN} (Pin 1/Pin 11): Signal Input Supply. Decouple this pin to SGND with a capacitor.

PGOOD (Pin 2/Pin 12): Power Good Output. Open-drain logic output that is pulled to ground when the output voltage is not within $\pm 7.5\%$ of regulation point.

I_{TH} (Pin 3/Pin 13): Error Amplifier Compensation Point. The current comparator threshold increases with this control voltage. Nominal voltage range for this pin is from 0.2V to 1.4V with 0.4V corresponding to the zero-sense voltage (zero current).

V_{FB} (Pin 4/Pin 14): Feedback Pin. Receives the feedback voltage from a resistive divider connected across the output.

R_T (Pin 5/Pin 15): Oscillator Resistor Input. Connecting a resistor to ground from this pin sets the switching frequency.

SYNC/MODE (Pin 6/Pin 16): Mode Select and External Clock Synchronization Input. To select forced continuous, tie to SV_{IN}. Connecting this pin to a voltage between 0V and 1V selects Burst Mode operation with the burst clamp set to the pin voltage.

RUN/SS (Pin 7/Pin 1): Run Control and Soft-Start Input. Forcing this pin below 0.5V shuts down the LTC3412A. In shutdown all functions are disabled drawing $< 1\mu\text{A}$ of supply current. A capacitor to ground from this pin sets the ramp time to full output current.

SGND (Pin 8/Pin 2): Signal Ground. All small-signal components, compensation components and the exposed pad on the bottom side of the IC should connect to this ground, which in turn connects to PGND at one point.

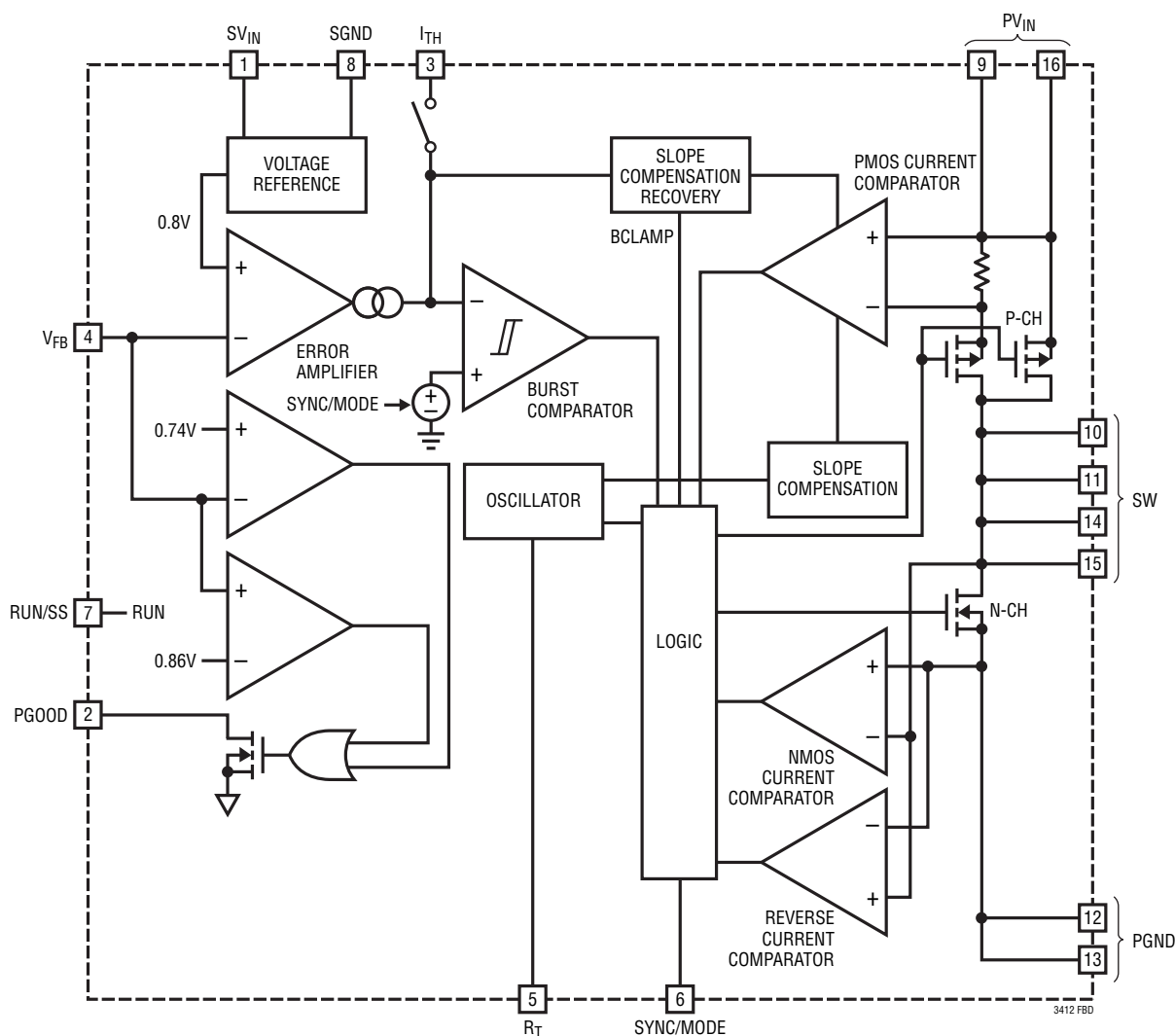
PV_{IN} (Pins 9, 16/Pins 3, 10): Power Input Supply. Decouple this pin to PGND with a capacitor.

SW (Pins 10, 11, 14, 15/Pins 4, 5, 8, 9): Switch Node Connection to the Inductor. This pin connects to the drains of the internal main and synchronous power MOSFET switches.

PGND (Pins 12, 13/Pins 6, 7): Power Ground. Connect this pin close to the (–) terminal of C_{IN} and C_{OUT}.

Exposed Pad (Pin 17/Pin 17): Signal Ground. Must be soldered to PCB for electrical connection and rated thermal performance.

FUNCTIONAL BLOCK DIAGRAM



OPERATION

Main Control Loop

The LTC3412A is a monolithic, constant-frequency, current mode step-down DC/DC converter. During normal operation, the internal top power switch (P-channel MOSFET) is turned on at the beginning of each clock cycle. Current in the inductor increases until the current comparator trips and turns off the top power MOSFET. The peak inductor current at which the current comparator shuts off the top power switch is controlled by the voltage on the I_{TH} pin. The error amplifier adjusts the voltage on the I_{TH} pin by

comparing the feedback signal from a resistor divider on the V_{FB} pin with an internal 0.8V reference. When the load current increases, it causes a reduction in the feedback voltage relative to the reference. The error amplifier raises the I_{TH} voltage until the average inductor current matches the new load current. When the top power MOSFET shuts off, the synchronous power switch (N-channel MOSFET) turns on until either the bottom current limit is reached or the beginning of the next clock cycle. The bottom current limit is set at $-1.3A$ for forced continuous mode and $0A$ for Burst Mode operation.

OPERATION

The operating frequency is externally set by an external resistor connected between the R_T pin and ground. The practical switching frequency can range from 300kHz to 4MHz.

Overvoltage and undervoltage comparators will pull the PGOOD output low if the output voltage comes out of regulation by $\pm 7.5\%$. In an overvoltage condition, the top power MOSFET is turned off and the bottom power MOSFET is switched on until either the overvoltage condition clears or the bottom MOSFET's current limit is reached.

Forced Continuous Mode

Connecting the SYNC/MODE pin to SV_{IN} will disable Burst Mode operation and force continuous current operation. At light loads, forced continuous mode operation is less efficient than Burst Mode operation, but may be desirable in some applications where it is necessary to keep switching harmonics out of a signal band. The output voltage ripple is minimized in this mode.

Burst Mode Operation

Connecting the SYNC/MODE pin to a voltage in the range of 0V to 1V enables Burst Mode operation. In Burst Mode operation, the internal power MOSFETs operate intermittently at light loads. This increases efficiency by minimizing switching losses. During Burst Mode operation, the minimum peak inductor current is externally set by the voltage on the SYNC/MODE pin and the voltage on the I_{TH} pin is monitored by the burst comparator to determine when sleep mode is enabled and disabled. When the average inductor current is greater than the load current, the voltage on the I_{TH} pin drops. As the I_{TH} voltage falls below 150mV, the burst comparator trips and enables sleep mode. During sleep mode, the top power MOSFET is held off and the I_{TH} pin is disconnected from the output of the error amplifier. The majority of the internal circuitry is also turned off to reduce the quiescent current to 64 μ A while the load current is solely supplied by the output capacitor. When the output voltage drops, the I_{TH} pin is reconnected to the output of the error amplifier and the top power MOSFET along with all the internal circuitry is switched back on. This process repeats at a rate that is dependent on the load demand.

Pulse-skipping operation is implemented by connecting the SYNC/MODE pin to ground. This forces the burst clamp level to be at 0V. As the load current decreases, the peak inductor current will be determined by the voltage on the I_{TH} pin until the I_{TH} voltage drops below 400mV. At this point, the peak inductor current is determined by the minimum on-time of the current comparator. If the load demand is less than the average of the minimum on-time inductor current, switching cycles will be skipped to keep the output voltage in regulation.

Frequency Synchronization

The internal oscillator of the LTC3412A can be synchronized to an external clock connected to the SYNC/MODE pin. The frequency of the external clock can be in the range of 300kHz to 4MHz. For this application, the oscillator timing resistor should be chosen to correspond to a frequency that is 25% lower than the synchronization frequency. During synchronization, the burst clamp is set to 0V, and each switching cycle begins at the falling edge of the clock signal.

Dropout Operation

When the input supply voltage decreases toward the output voltage, the duty cycle increases toward the maximum on-time. Further reduction of the supply voltage forces the main switch to remain on for more than one cycle eventually reaching 100% duty cycle. The output voltage will then be determined by the input voltage minus the voltage drop across the internal P-channel MOSFET and the inductor.

Low Supply Operation

The LTC3412A is designed to operate down to an input supply voltage of 2.25V. One important consideration at low input supply voltages is that the $R_{DS(ON)}$ of the P-channel and N-channel power switches increases. The user should calculate the power dissipation when the LTC3412A is used at 100% duty cycle with low input voltages to ensure that thermal limits are not exceeded.

APPLICATIONS INFORMATION

Slope Compensation and Inductor Peak Current

Slope compensation provides stability in constant frequency architectures by preventing subharmonic oscillations at duty cycles greater than 50%. It is accomplished internally by adding a compensating ramp to the inductor current signal at duty cycles in excess of 40%. Normally, the maximum inductor peak current is reduced when slope compensation is added. In the LTC3412A, however, slope compensation recovery is implemented to keep the maximum inductor peak current constant throughout the range of duty cycles. This keeps the maximum output current relatively constant regardless of duty cycle.

Short-Circuit Protection

When the output is shorted to ground, the inductor current decays very slowly during a single switching cycle. To prevent current runaway from occurring, a secondary current limit is imposed on the inductor current. If the inductor valley current increases larger than 4.4A, the top power MOSFET will be held off and switching cycles will be skipped until the inductor current is reduced.

The basic LTC3412A application circuit is shown in Figure 1. External component selection is determined by the maximum load current and begins with the selection of the operating frequency and inductor value followed by C_{IN} and C_{OUT} .

Operating Frequency

Selection of the operating frequency is a trade-off between efficiency and component size. High frequency operation allows the use of smaller inductor and capacitor values. Operation at lower frequencies improves efficiency by reducing internal gate charge losses but requires larger inductance values and/or capacitance to maintain low output ripple voltage.

The operating frequency of the LTC3412A is determined by an external resistor that is connected between pin R_T and ground. The value of the resistor sets the ramp current that is used to charge and discharge an internal timing capacitor within the oscillator and can be calculated by using the following equation:

$$R_{OSC} = \frac{3.08 \cdot 10^{11}}{f} (\Omega) - 10k\Omega$$

Although frequencies as high as 4MHz are possible, the minimum on-time of the LTC3412A imposes a minimum limit on the operating duty cycle. The minimum on-time is typically 110ns; therefore, the minimum duty cycle is equal to $100 \cdot 110ns \cdot f(Hz)$.

Inductor Selection

For a given input and output voltage, the inductor value and operating frequency determine the ripple current. The ripple current ΔI_L increases with higher V_{IN} or V_{OUT} and decreases with higher inductance.

$$\Delta I_L = \left(\frac{V_{OUT}}{fL} \right) \left(1 - \frac{V_{OUT}}{V_{IN}} \right)$$

Having a lower ripple current reduces the core losses in the inductor, the ESR losses in the output capacitors, and the output voltage ripple. Highest efficiency operation is achieved at low frequency with small ripple current. This, however, requires a large inductor.

A reasonable starting point for selecting the ripple current is $\Delta I_L = 0.4(I_{MAX})$. The largest ripple current occurs at the highest V_{IN} . To guarantee that the ripple current stays below a specified maximum, the inductor value should be chosen according to the following equation:

$$L = \left(\frac{V_{OUT}}{f\Delta I_{L(MAX)}} \right) \left(1 - \frac{V_{OUT}}{V_{IN(MAX)}} \right)$$

The inductor value will also have an effect on Burst Mode operation. The transition to low current operation begins when the peak inductor current falls below a level set by the burst clamp. Lower inductor values result in higher ripple current which causes this to occur at lower load currents. This causes a dip in efficiency in the upper range of low current operation. In Burst Mode operation, lower inductance values will cause the burst frequency to increase.

Inductor Core Selection

Once the value for L is known, the type of inductor must be selected. Actual core loss is independent of core size for a fixed inductor value, but it is very dependent on the inductance selected. As the inductance increases, core losses decrease. Unfortunately, increased inductance requires more turns of wire and therefore copper losses will increase.

APPLICATIONS INFORMATION

Ferrite designs have very low core losses and are preferred at high switching frequencies, so design goals can concentrate on copper loss and preventing saturation. Ferrite core material saturates “hard,” which means that inductance collapses abruptly when the peak design current is exceeded. This results in an abrupt increase in inductor ripple current and consequent output voltage ripple. Do not allow the core to saturate!

Different core materials and shapes will change the size/current and price/current relationship of an inductor. Toroid or shielded pot cores in ferrite or permalloy materials are small and don’t radiate much energy, but generally cost more than powdered iron core inductors with similar characteristics. The choice of which style inductor to use mainly depends on the price versus size requirements and any radiated field/EMI requirements. New designs for surface mount inductors are available from Coiltronics, Coilcraft, Toko and Sumida.

C_{IN} and C_{OUT} Selection

The input capacitance, C_{IN}, is needed to filter the trapezoidal wave current at the source of the top MOSFET. To prevent large voltage transients from occurring, a low ESR input capacitor sized for the maximum RMS current should be used. The maximum RMS current is given by:

$$I_{\text{RMS}} = I_{\text{OUT(MAX)}} \frac{V_{\text{OUT}}}{V_{\text{IN}}} \sqrt{\frac{V_{\text{IN}}}{V_{\text{OUT}}} - 1}$$

This formula has a maximum at $V_{\text{IN}} = 2V_{\text{OUT}}$, where $I_{\text{RMS}} = I_{\text{OUT}}/2$. This simple worst-case condition is commonly used for design because even significant deviations do not offer much relief. Note that ripple current ratings from capacitor manufacturers are often based on only 2000 hours of life which makes it advisable to further derate the capacitor, or choose a capacitor rated at a higher temperature than required. Several capacitors may also be paralleled to meet size or height requirements in the design. For low input voltage applications, sufficient bulk input capacitance is needed to minimize transient effects during output load changes.

The selection of C_{OUT} is determined by the effective series resistance (ESR) that is required to minimize voltage ripple and load step transients as well as the amount of bulk

capacitance that is necessary to ensure that the control loop is stable. Loop stability can be checked by viewing the load transient response as described in a later section. The output ripple, ΔV_{OUT} , is determined by:

$$\Delta V_{\text{OUT}} \leq \Delta I_L \left(\text{ESR} + \frac{1}{8fC_{\text{OUT}}} \right)$$

The output ripple is highest at maximum input voltage since ΔI_L increases with input voltage. Multiple capacitors placed in parallel may be needed to meet the ESR and RMS current handling requirements. Dry tantalum, special polymer, aluminum electrolytic, and ceramic capacitors are all available in surface mount packages. Special polymer capacitors offer very low ESR but have lower capacitance density than other types. Tantalum capacitors have the highest capacitance density but it is important to only use types that have been surge tested for use in switching power supplies. Aluminum electrolytic capacitors have significantly higher ESR, but can be used in cost-sensitive applications provided that consideration is given to ripple current ratings and long-term reliability. Ceramic capacitors have excellent low ESR characteristics but can have a high voltage coefficient and audible piezoelectric effects. The high Q of ceramic capacitors with trace inductance can also lead to significant ringing.

Using Ceramic Input and Output Capacitors

Higher values, lower cost ceramic capacitors are now becoming available in smaller case sizes. Their high ripple current, high voltage rating and low ESR make them ideal for switching regulator applications. However, care must be taken when these capacitors are used at the input and output. When a ceramic capacitor is used at the input and the power is supplied by a wall adapter through long wires, a load step at the output can induce ringing at the input, V_{IN} . At best, this ringing can couple to the output and be mistaken as loop instability. At worst, a sudden inrush of current through the long wires can potentially cause a voltage spike at V_{IN} large enough to damage the part.

When choosing the input and output ceramic capacitors, choose the X5R or X7R dielectric formulations. These dielectrics have the best temperature and voltage characteristics of all the ceramics for a given value and size.

APPLICATIONS INFORMATION

Output Voltage Programming

The output voltage is set by an external resistive divider according to the following equation:

$$V_{OUT} = 0.8V \left(1 + \frac{R2}{R1} \right)$$

The resistive divider allows pin V_{FB} to sense a fraction of the output voltage as shown in Figure 2.

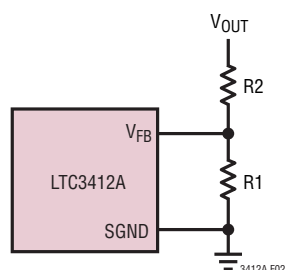


Figure 2. Setting the Output Voltage

Burst Clamp Programming

If the voltage on the SYNC/MODE pin is less than V_{IN} by 1V, Burst Mode operation is enabled. During Burst Mode Operation, the voltage on the SYNC/MODE pin determines the burst clamp level, which sets the minimum peak inductor current, I_{BURST} . To select the burst clamp level, use the graph of Minimum Peak Inductor Current vs Burst Clamp Voltage in the Typical Performance Characteristics section.

V_{BURST} is the voltage on the SYNC/MODE pin. I_{BURST} can only be programmed in the range of 0A to 6A. For values of V_{BURST} greater than 1V, I_{BURST} is set at 6A. For values of V_{BURST} less than 0.4V, I_{BURST} is set at 0A. As the output load current drops, the peak inductor currents decrease to keep the output voltage in regulation. When the output load current demands a peak inductor current that is less than I_{BURST} , the burst clamp will force the peak inductor current to remain equal to I_{BURST} regardless of further reductions in the load current. Since the average inductor current is greater than the output load current, the voltage on the I_{TH} pin will decrease. When the I_{TH} voltage drops to 150mV, sleep mode is enabled in which both power MOSFETs are shut off along with most of the circuitry to minimize power consumption. All circuitry is turned back on and the power MOSFETs begin switching again when the output voltage drops out of regulation.

The value for I_{BURST} is determined by the desired amount of output voltage ripple. As the value of I_{BURST} increases, the sleep period between pulses and the output voltage ripple increase. The burst clamp voltage, V_{BURST} , can be set by a resistor divider from the V_{FB} pin to the SGND pin as shown in Figure 1.

Pulse skipping, which is a compromise between low output voltage ripple and efficiency, can be implemented by connecting pin SYNC/MODE to ground. This sets I_{BURST} to 0A. In this condition, the peak inductor current is limited by the minimum on-time of the current comparator. The lowest output voltage ripple is achieved while still operating discontinuously. During very light output loads, pulse skipping allows only a few switching cycles to be skipped while maintaining the output voltage in regulation.

Frequency Synchronization

The LTC3412A's internal oscillator can be synchronized to an external clock signal. During synchronization, the top MOSFET turn-on is locked to the **falling** edge of the external frequency source. The synchronization frequency range is 300kHz to 4MHz. Synchronization only occurs if the external frequency is greater than the frequency set by the external resistor. Because slope compensation is generated by the oscillator's RC circuit, the external frequency should be set 25% higher than the frequency set by the external resistor to ensure that adequate slope compensation is present.

Soft-Start

The RUN/SS pin provides a means to shut down the LTC3412A as well as a timer for soft-start. Pulling the RUN/SS pin below 0.5V places the LTC3412A in a low quiescent current shutdown state ($I_Q < 1\mu A$).

The LTC3412A contains an internal soft-start clamp that gradually raises the clamp on I_{TH} after the RUN/SS pin is pulled above 2V. The full current range becomes available on I_{TH} after 1024 switching cycles. If a longer soft-start period is desired, the clamp on I_{TH} can be set externally with a resistor and capacitor on the RUN/SS pin as shown in Figure 1. The soft-start duration can be calculated by using the following formula:

$$t_{SS} = R_{SS} C_{SS} \ln \left(\frac{V_{IN}}{V_{IN} - 1.8V} \right) \text{ (SECONDS)}$$

APPLICATIONS INFORMATION

Efficiency Considerations

The efficiency of a switching regulator is equal to the output power divided by the input power times 100%. It is often useful to analyze individual losses to determine what is limiting the efficiency and which change would produce the most improvement. Efficiency can be expressed as:

$$\text{Efficiency} = 100\% - (L1 + L2 + L3 + \dots)$$

where L1, L2, etc. are the individual losses as a percentage of input power.

Although all dissipative elements in the circuit produce losses, two main sources usually account for most of the losses: V_{IN} quiescent current and I^2R losses.

The V_{IN} quiescent current loss dominates the efficiency loss at very low load currents whereas the I^2R loss dominates the efficiency loss at medium to high load currents. In a typical efficiency plot, the efficiency curve at very low load currents can be misleading since the actual power lost is of no consequence.

1. The V_{IN} quiescent current is due to two components: the DC bias current as given in the electrical characteristics and the internal main switch and synchronous switch gate charge currents. The gate charge current results from switching the gate capacitance of the internal power MOSFET switches. Each time the gate is switched from high to low to high again, a packet of charge dQ moves from V_{IN} to ground. The resulting dQ/dt is the current out of V_{IN} that is typically larger than the DC bias current. In continuous mode, $I_{GATECHG} = f(QT + QB)$ where QT and QB are the gate charges of the internal top and bottom switches. Both the DC bias and gate charge losses are proportional to V_{IN} ; thus, their effects will be more pronounced at higher supply voltages.
2. I^2R losses are calculated from the resistances of the internal switches, R_{SW} , and external inductor R_L . In continuous mode the average output current flowing through inductor L is “chopped” between the main switch and the synchronous switch. Thus, the series resistance looking into the SW pin is a function of both top and bottom MOSFET $R_{DS(ON)}$ and the duty cycle (DC) as follows:

$$R_{SW} = (R_{DS(ON)TOP})(DC) + (R_{DS(ON)BOT})(1 - DC)$$

The $R_{DS(ON)}$ for both the top and bottom MOSFETs can be obtained from the Typical Performance Characteristics curves. To obtain I^2R losses, simply add R_{SW} to R_L and multiply the result by the square of the average output current.

Other losses including C_{IN} and C_{OUT} ESR dissipative losses and inductor core losses generally account for less than 2% of the total loss.

Thermal Considerations

In most applications, the LTC3412A does not dissipate much heat due to its high efficiency.

However, in applications where the LTC3412A is running at high ambient temperature with low supply voltage and high duty cycles, such as in dropout, the heat dissipated may exceed the maximum junction temperature of the part. If the junction temperature reaches approximately 150°C, both power switches will be turned off and the SW node will become high impedance.

To avoid the LTC3412A from exceeding the maximum junction temperature, the user will need to do some thermal analysis. The goal of the thermal analysis is to determine whether the power dissipated exceeds the maximum junction temperature of the part. The temperature rise is given by:

$$t_r = (P_D)(\theta_{JA})$$

where P_D is the power dissipated by the regulator and θ_{JA} is the thermal resistance from the junction of the die to the ambient temperature. For the 16-lead exposed TSSOP package, the θ_{JA} is 38°C/W. For the 16-lead QFN package the θ_{JA} is 34°C/W.

The junction temperature, T_J , is given by:

$$T_J = T_A + t_r$$

where T_A is the ambient temperature.

Note that at higher supply voltages, the junction temperature is lower due to reduced switch resistance ($R_{DS(ON)}$). To maximize the thermal performance of the LTC3412A, the Exposed Pad should be soldered to a ground plane.

Checking Transient Response

The regulator loop response can be checked by looking at the load transient response. Switching regulators take several cycles to respond to a step in load current.

APPLICATIONS INFORMATION

When a load step occurs, V_{OUT} immediately shifts by an amount equal to $\Delta I_{LOAD}(ESR)$, where ESR is the effective series resistance of C_{OUT} . ΔI_{LOAD} also begins to charge or discharge C_{OUT} generating a feedback error signal used by the regulator to return V_{OUT} to its steady-state value. During this recovery time, V_{OUT} can be monitored for overshoot or ringing that would indicate a stability problem. The I_{TH} pin external components and output capacitor shown in Figure 1 will provide adequate compensation for most applications.

Design Example

As a design example, consider using the LTC3412A in an application with the following specifications:

$$V_{IN} = 3.3V, V_{OUT} = 2.5V, I_{OUT(MAX)} = 3A, \\ I_{OUT(MIN)} = 100mA, f = 1MHz.$$

Because efficiency is important at both high and low load current, Burst Mode operation will be utilized.

First, calculate the timing resistor:

$$R_{OSC} = \frac{3.08 \cdot 10^{11}}{1 \cdot 10^6} - 10k = 298k$$

Use a standard value of 294k. Next, calculate the inductor value for about 40% ripple current at maximum V_{IN} :

$$L = \left(\frac{2.5V}{(1MHz)(1.2A)} \right) \left(1 - \frac{2.5V}{3.3V} \right) = 0.51\mu H$$

Using a 0.47 μ H inductor results in a maximum ripple current of:

$$\Delta I_L = \left(\frac{2.5V}{(1MHz)(0.47\mu H)} \right) \left(1 - \frac{2.5V}{3.3V} \right) = 1.29A$$

C_{OUT} will be selected based on the ESR that is required to satisfy the output voltage ripple requirement and the bulk capacitance needed for loop stability. For this design, two 100 μ F ceramic capacitors will be used.

C_{IN} should be sized for a maximum current rating of:

$$I_{RMS} = (3A) \left(\frac{2.5V}{3.3V} \right) \sqrt{\frac{3.3V}{2.5V} - 1} = 1.29A_{RMS}$$

Decoupling the PV_{IN} and SV_{IN} pins with two 22 μ F capacitors is adequate for most applications.

The burst clamp and output voltage can now be programmed by choosing the values of R1, R2 and R3. The voltage on pin MODE will be set to 0.50V by the resistor divider consisting of R2 and R3. According to the graph of Minimum Peak Inductor Current vs Burst Clamp Voltage in the Typical Performance Characteristics section, a burst clamp voltage of 0.5V will set the minimum inductor current, I_{BURST} , to approximately 1.1A.

If we set the sum of R2 and R3 to 185k, then the following equations can be solved:

$$R2 + R3 = 185k$$

$$1 + \frac{R2}{R3} = \frac{0.8V}{0.50V}$$

The two equations shown above result in the following values for R2 and R3: R2 = 69.8k, R3 = 115k. The value of R1 can now be determined by solving the following equation.

$$1 + \frac{R1}{185k} = \frac{2.5V}{0.8V}$$

$$R1 = 392k$$

A value of 392k will be selected for R1. Figure 4 shows the complete schematic for this design example.

PC Board Layout Checklist

When laying out the printed circuit board, the following checklist should be used to ensure proper operation of the LTC3412A. Check the following in your layout:

1. A ground plane is recommended. If a ground plane layer is not used, the signal and power grounds should be segregated with all small signal components returning to the SGND pin at one point which is then connected to the PGND pin close to the LTC3412A.
2. Connect the (+) terminal of the input capacitor(s), C_{IN} , as close as possible to the PV_{IN} pin. This capacitor provides the AC current into the internal power MOSFETs.

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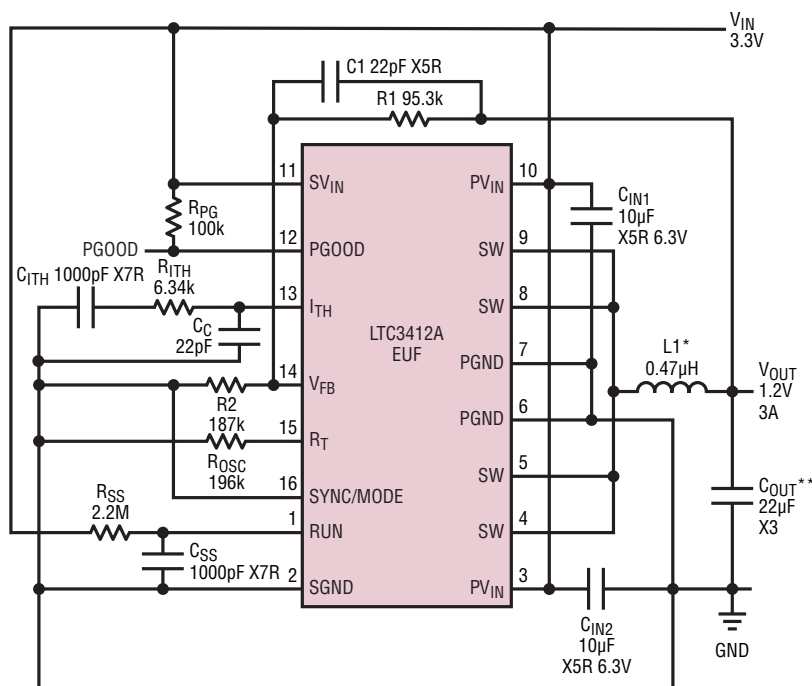
A 10x10 grid world environment. The grid contains several obstacles represented by black shapes: a large black circle at (1,1), a small black square at (2,2), two small black circles at (2,3) and (2,4), a small black square at (3,2), two small black circles at (3,3) and (3,4), a large black circle at (1,10), a small black square at (2,10), a small black circle at (2,9), a small black square at (3,10), a small black circle at (3,9), a large black circle at (4,10), a small black square at (5,10), a small black circle at (5,9), a small black square at (6,10), a small black circle at (6,9), a large black circle at (7,10), a small black square at (8,10), a small black circle at (8,9), a small black square at (9,10), a small black circle at (9,9), a large black circle at (10,10), a small black square at (10,9), a small black circle at (10,8), a small black square at (10,7), a small black circle at (10,6), a small black square at (10,5), a small black circle at (10,4), a small black square at (10,3), a small black circle at (10,2), a small black square at (10,1), a small black circle at (9,1), a small black square at (8,1), a small black circle at (7,1), a small black square at (6,1), a small black circle at (5,1), a small black square at (4,1), a small black circle at (3,1), a small black square at (2,1), a small black circle at (1,2), a small black square at (1,3), a small black circle at (1,4), a small black square at (1,5), a small black circle at (1,6), a small black square at (1,7), a small black circle at (1,8), a small black square at (1,9), a small black circle at (1,10). The goal is represented by a small black circle at (5,5). The start is represented by a small black circle at (5,5).

*VISHAY IHLP-2525CZ-01
 **TDK 4532X5R0J107M

3412 F04

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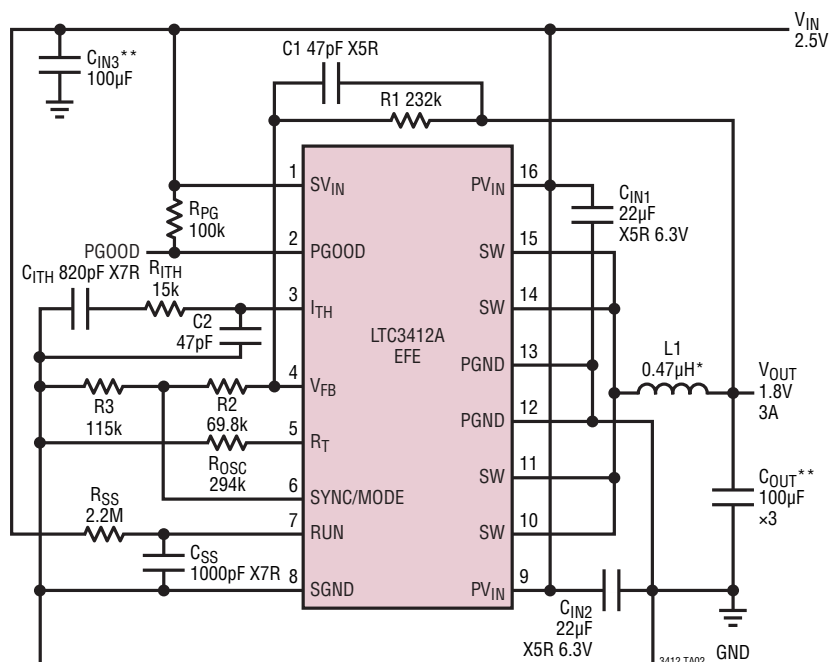
1.2V, 3A, 1.5MHz 1mm Height Regulator Using All Ceramic Capacitors



*COOPER SD10-R47

**TAIYO YUDEN AMK212BJ226MD-B

1.8V, 3A Step-Down Regulator at 1MHz, Burst Mode Operation

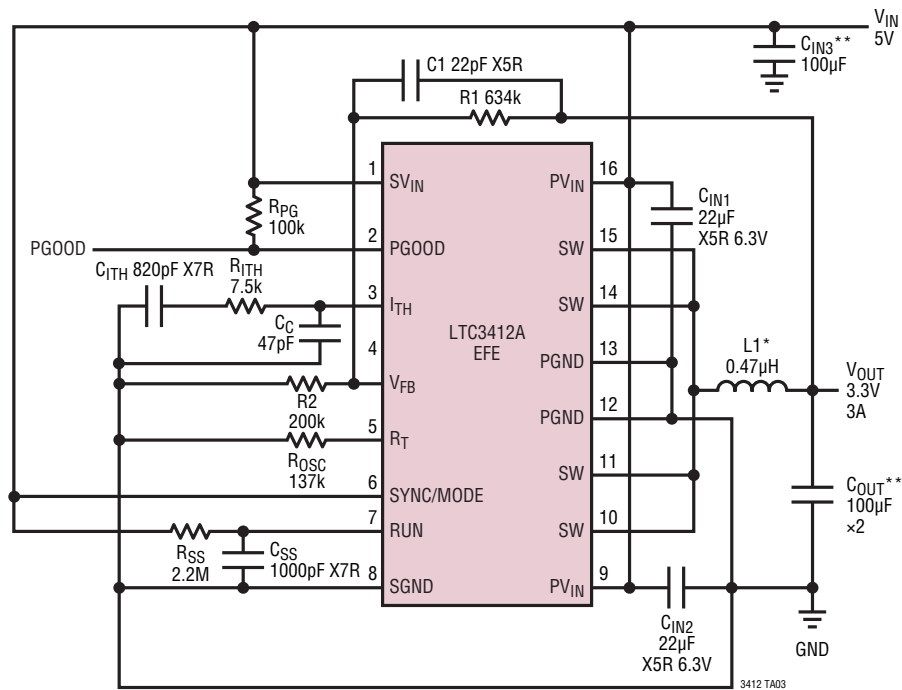


*VISHAY IHL-2525CZ-01

**TDK C4532X5R0J107M

TYPICAL APPLICATIONS

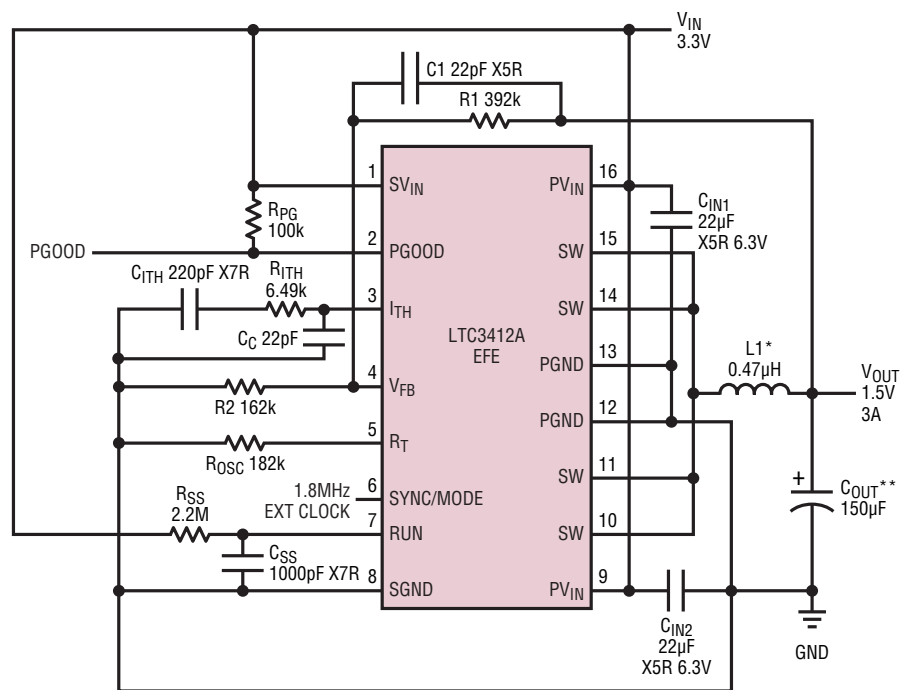
3.3V, 3A Step-Down Regulator at 2MHz, Forced Continuous Mode Operation



*VISHAY IHLP-2525CZ-01

**TDK C4532X5R0J107M

2.5V, 3A Step-Down Regulator Synchronized to 1.8MHz

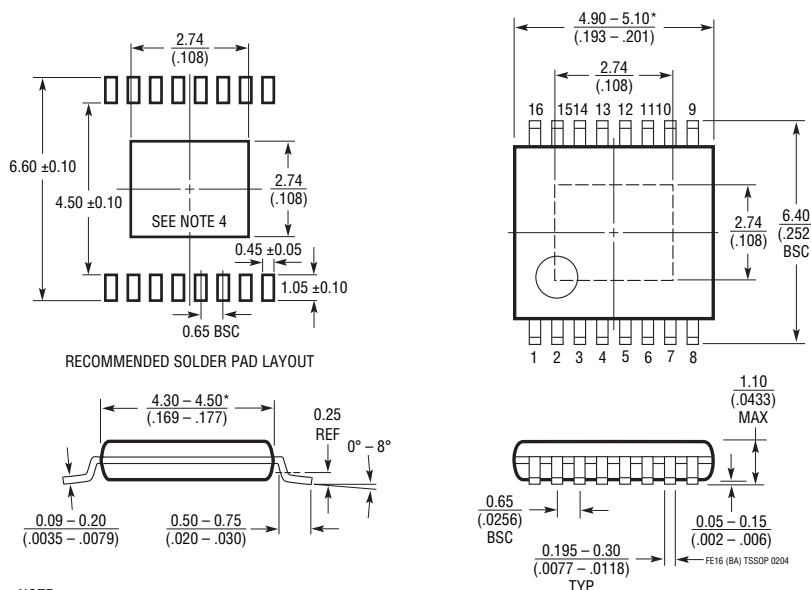


*COOPER SD20-R47

**SANYO POSCAP 4TPE150MAZB

PACKAGE DESCRIPTION

FE Package
16-Lead Plastic TSSOP (4.4mm)
 (Reference LTC DWG # 05-08-1663)
Exposed Pad Variation BA



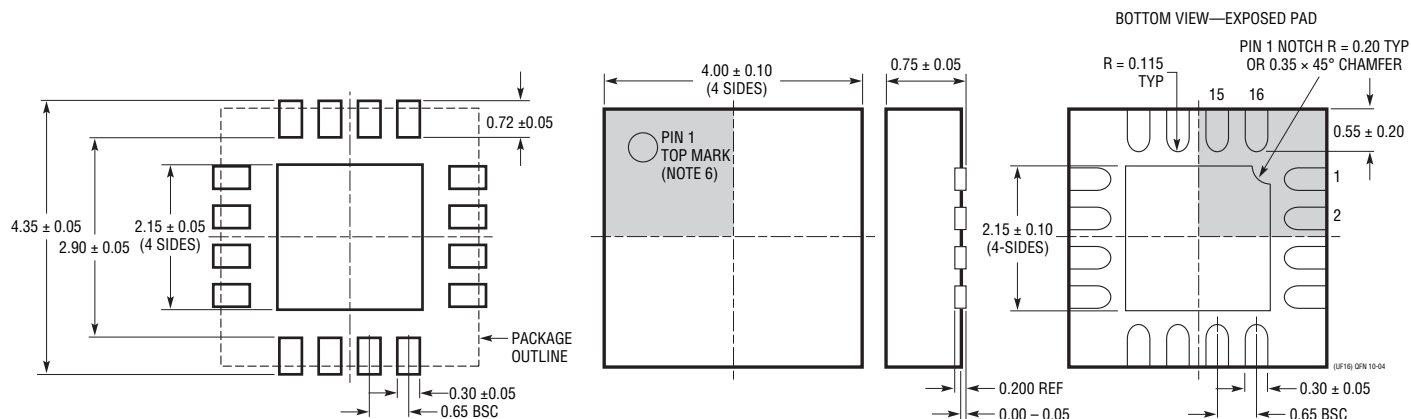
NOTE:

1. CONTROLLING DIMENSION: MILLIMETERS
2. DIMENSIONS ARE IN MILLIMETERS (INCHES)
3. DRAWING NOT TO SCALE

4. RECOMMENDED MINIMUM PCB METAL SIZE FOR EXPOSED PAD ATTACHMENT

*DIMENSIONS DO NOT INCLUDE MOLD FLASH. MOLD FLASH SHALL NOT EXCEED 0.150mm (.006") PER SIDE

UF Package
16-Lead Plastic QFN (4mm × 4mm)
 (Reference LTC DWG # 05-08-1692)



NOTE:

1. DRAWING CONFORMS TO JEDEC PACKAGE OUTLINE MO-220 VARIATION (WGCC)
2. DRAWING NOT TO SCALE
3. ALL DIMENSIONS ARE IN MILLIMETERS
4. DIMENSIONS OF EXPOSED PAD ON BOTTOM OF PACKAGE DO NOT INCLUDE MOLD FLASH. MOLD FLASH, IF PRESENT, SHALL NOT EXCEED 0.15mm ON ANY SIDE
5. EXPOSED PAD SHALL BE SOLDER PLATED
6. SHADED AREA IS ONLY A REFERENCE FOR PIN 1 LOCATION ON THE TOP AND BOTTOM OF PACKAGE

REVISION HISTORY (Revision history begins at Rev E)

REV	DATE	DESCRIPTION	PAGE NUMBER
E	03/10	Changed Temperature Range for E- and I-Grades to -40°C to 125°C in Absolute Maximum Ratings and Order Information Sections	2
		Changed from $T_A = 25^{\circ}\text{C}$ to $T_A \approx T_J = 25^{\circ}\text{C}$ in the Electrical Characteristics Heading	3
		Updated Note 2	3

RELATED PARTS

PART NUMBER	DESCRIPTION	COMMENTS
LTC1878	600mA (I_{OUT}), 550kHz, Synchronous Step-Down DC/DC Converter	96% Efficiency, V_{IN} : 2.7V to 6V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 10\mu A$, $I_{SD} < 1\mu A$, MS8 Package
LTC1879	1.20A (I_{OUT}), 550kHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.7V to 10V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 15\mu A$, $I_{SD} < 1\mu A$, TSSOP16 Package
LT1934/LT1934-1	300mA (I_{OUT}), Constant Off-Time, High Efficiency Step-Down DC/DC Converter	90% Efficiency, V_{IN} : 3.2V to 34V, $V_{OUT(MIN)} = 1.25V$, $I_Q = 14\mu A$, $I_{SD} < 1\mu A$, ThinSOT™ Package
LTC3404	600mA (I_{OUT}), 1.4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.7V to 6V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 10\mu A$, $I_{SD} < 1\mu A$, MS8 Package
LTC3405/LTC3405A	300mA (I_{OUT}), 1.5MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 20\mu A$, $I_{SD} < 1\mu A$, ThinSOT Package
LTC3406/LTC3406B	600mA (I_{OUT}), 1.5MHz, Synchronous Step-Down DC/DC Converter	96% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.6V$, $I_Q = 20\mu A$, $I_{SD} < 1\mu A$, ThinSOT Package
LTC3407	Dual 600mA (I_{OUT}), 1.5MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.6V$, $I_Q = 40\mu A$, $I_{SD} < 1\mu A$, MS10E and 3mm × 3mm DFN Packages
LTC3411	1.25A (I_{OUT}), 4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 60\mu A$, $I_{SD} < 1\mu A$, MS10 and 3mm × 3mm DFN Packages
LTC3412	2.5A (I_{OUT}), 4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 60\mu A$, $I_{SD} < 1\mu A$, TSSOP16E Package
LTC3413	3A (I_{OUT} Sink/Source), 2MHz, Monolithic Synchronous Regulator for DDR/QDR Memory Termination	90% Efficiency, V_{IN} : 2.25V to 5.5V, $V_{OUT(MIN)} = V_{REF}/2$, $I_Q = 280\mu A$, $I_{SD} < 1\mu A$, TSSOP16E Package
LTC3414	4A (I_{OUT}), 4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.25V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 64\mu A$, $I_{SD} < 1\mu A$, TSSOP20E Package
LTC3416	4A (I_{OUT}), 4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.25V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 64\mu A$, $I_{SD} < 1\mu A$, TSSOP20E Package
LTC3418	8A (I_{OUT}), 4MHz, Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.25V to 5.5V, $V_{OUT(MIN)} = 0.8V$, $I_Q = 380\mu A$, $I_{SD} < 1\mu A$, QFN Package
LT3430	60V, 2.75A (I_{OUT}), 200kHz, High Efficiency Step-Down DC/DC Converter	90% Efficiency, V_{IN} : 5.5V to 60V, $V_{OUT(MIN)} = 1.20V$, $I_Q = 2.5mA$, $I_{SD} 25\mu A$, TSSOP16E Package
LTC3440	600mA (I_{OUT}), 2MHz, Synchronous Buck-Boost DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, V_{OUT} : 2.5V to 5.5V, $I_Q = 25\mu A$, $I_{SD} < 1\mu A$, DFN Package
LTC3441	1.2A (I_{OUT}), 1MHz, Synchronous Buck-Boost DC/DC Converter	95% Efficiency, V_{IN} : 2.4V to 5.5V, V_{OUT} : 2.4V to 5.25V, $I_Q = 25\mu A$, $I_{SD} < 1\mu A$, DFN Package
LTC3548	400mA/800mA Dual Synchronous Step-Down DC/DC Converter	95% Efficiency, V_{IN} : 2.5V to 5.5V, $V_{OUT(MIN)} = 0.6V$, $I_Q < 40\mu A$, $I_{SD} < 1\mu A$, MS8E and DFN Packages