High Efficiency Low-Side N-Channel Controller for Switching Regulators

Check for Samples: LM3488, LM3488-Q1

FEATURES

- **LM3488Q is AEC-Q100 qualified and manufactured on an Automotive Grade Flow**
- **8-lead VSSOP package**
- **Internal push-pull driver with 1A peak current capability**
- **Current limit and thermal shutdown**
- **Frequency compensation optimized with a capacitor and a resistor**
- **Internal softstart**
- **Current Mode Operation**
- **Undervoltage Lockout with hysteresis**

APPLICATIONS

- **Distributed Power Systems**
- **Notebook, PDA, Digital Camera, and other Portable Applications**
- **Offline Power Supplies**
- **Set-Top Boxes**

DESCRIPTION

The LM3488 is a versatile Low-Side N-FET high performance controller for switching regulators. It is suitable for use in topologies requiring low side FET, such as boost, flyback, or SEPIC. Moreover, the LM3488 can be operated at extremely high switching frequency in order to reduce the overall solution size. The switching frequency of LM3488 can be adjusted to any value between 100kHz and 1MHz by using a single external resistor or by synchronizing it to an external clock. Current mode control provides superior bandwidth and transient response, besides cycle-by-cycle current limiting. Output current can be programmed with a single external resistor.

The LM3488 has built in features such as thermal shutdown, short-circuit protection and over voltage protection. Power saving shutdown mode reduces the total supply current to 5µA and allows power supply sequencing. Internal soft-start limits the inrush current at start-up.

KEY SPECIFICATIONS

- **Wide supply voltage range of 2.97V to 40V**
- **100kHz to 1MHz Adjustable and Synchronizable clock frequency**
- **±1.5% (over temperature) internal reference**
- **5µA shutdown current (over temperature)**

TYPICAL APPLICATION CIRCUIT

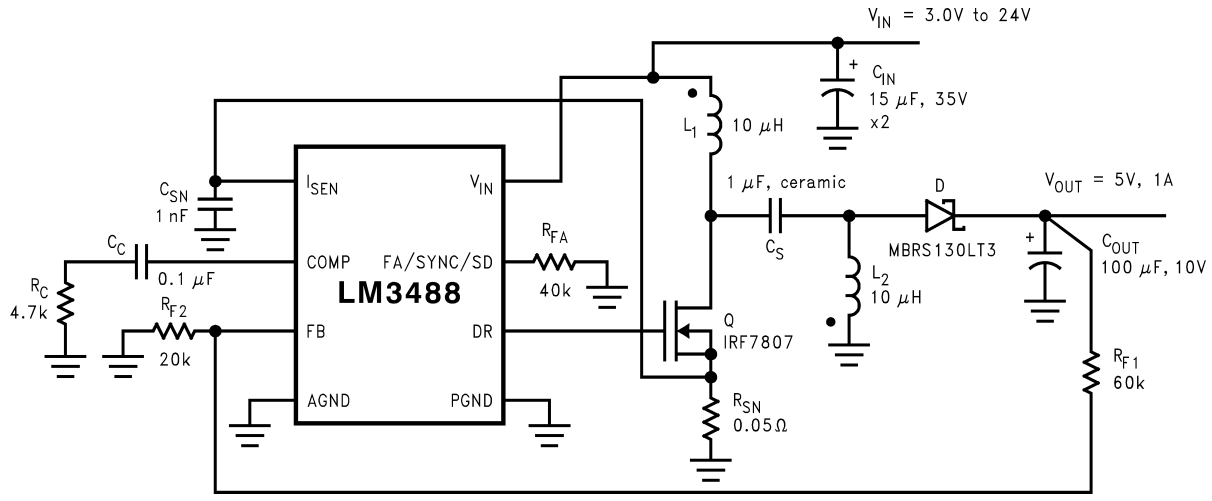

Figure 1. Typical SEPIC Converter

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Connection Diagram

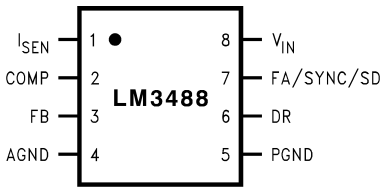


Figure 2. 8-Lead VSSOP Package

PIN DESCRIPTIONS

Pin Name	Pin No.	Description
I_{SEN}	1	Current sense input pin. Voltage generated across an external sense resistor is fed into this pin.
COMP	2	Compensation pin. A resistor, capacitor combination connected to this pin provides compensation for the control loop.
FB	3	Feedback pin. The output voltage should be adjusted using a resistor divider to provide 1.26V at this pin.
AGND	4	Analog ground pin.
PGND	5	Power ground pin.
DR	6	Drive pin of the IC. The gate of the external MOSFET should be connected to this pin.
FA/SYNC/SD	7	Frequency adjust, synchronization, and Shutdown pin. A resistor connected to this pin sets the oscillator frequency. An external clock signal at this pin will synchronize the controller to the frequency of the clock. A high level on this pin for ≥ 30µs will turn the device off. The device will then draw less than 10µA from the supply.
V_{IN}	8	Power supply input pin.

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

Absolute Maximum Ratings (1)

Input Voltage		45V
FB Pin Voltage		-0.4V < V_{FB} < 7V
FA/SYNC/SD Pin Voltage		-0.4V < $V_{FA/SYNC/SD}$ < 7V
Peak Driver Output Current (<10µs)		1.0A
Power Dissipation		Internally Limited
Storage Temperature Range		−65°C to +150°C
Junction Temperature		+150°C
ESD Susceptibilty	Human Body Model(2)	2kV
Lead Temperature	Vapor Phase (60 sec.)	215°C
	Infared (15 sec.)	260°C
DR Pin Voltage		−0.4V ≤ VDR ≤ 8V
I_{LIM} Pin Voltage		600mV

(1) Absolute Maximum Ratings are limits beyond which damage to the device may occur. Operating Ratings are conditions under which operation of the device is intended to be functional. For specifications and test conditions, see the Electrical Characteristics.
(2) The human body model is a 100 pF capacitor discharged through a 1.5kΩ resistor into each pin.

Operating Ratings (1)

Supply Voltage	$2.97V \le V_{IN} \le 40V$
Junction Temperature Range	$-40°C \le T_J \le +125°C$
Switching Frequency	$100kHz \le F_{SW} \le 1MHz$

(1) Absolute Maximum Ratings are limits beyond which damage to the device may occur. Operating Ratings are conditions under which operation of the device is intended to be functional. For specifications and test conditions, see the Electrical Characteristics.

Electrical Characteristics

Specifications in Standard type face are for T_J = 25°C, and in **bold type face** apply over the full **Operating Temperature Range**. Unless otherwise specified, V_{IN} = 12V, R_{FA} = 40kΩ

Symbol	Parameter	Conditions	Typical	Limit	Unit
V_{FB}	Feedback Voltage	V_{COMP} = 1.4V, 2.97 ≤ V_{IN} ≤ 40V	1.26	1.2507/**1.24** 1.2753/**1.28**	V V(min) V(max)
ΔV_{LINE}	Feedback Voltage Line Regulation	2.97 ≤ V_{IN} ≤ 40V	0.001		%/V
ΔV_{LOAD}	Output Voltage Load Regulation	I_{EAO} Source/Sink	±0.5		%/V (max)
V_{UVLO}	Input Undervoltage Lock-out		2.85	**2.97**	V V(max)
$V_{UV(HYS)}$	Input Undervoltage Lock-out Hysteresis		170	**130** **210**	mV mV (min) mV (max)
F_{nom}	Nominal Switching Frequency	R_{FA} = 40KΩ	400	**360** **430**	kHz kHz(min) kHz(max)
$R_{DS1\ (ON)}$	Driver Switch On Resistance (top)	I_{DR} = 0.2A, V_{IN}= 5V	16		Ω
$R_{DS2\ (ON)}$	Driver Switch On Resistance (bottom)	I_{DR} = 0.2A	4.5		Ω
$V_{DR\ (max)}$	Maximum Drive Voltage Swing (1)	V_{IN} < 7.2V	V_{IN}		V
		V_{IN} ≥ 7.2V	7.2		
D_{max}	Maximum Duty Cycle (2)		100		%
T_{min} (on)	Minimum On Time		325	**230** **550**	nsec nsec(min) nsec(max)
I_{SUPPLY}	Supply Current (switching)	(3)	2.7	**3.0**	mA mA (max)
I_Q	Quiescent Current in Shutdown Mode	$V_{FA/SYNC/SD}$ = 5V (4), V_{IN} = 5V	5	**7**	µA µA (max)
V_{SENSE}	Current Sense Threshold Voltage	V_{IN} = 5V	156	135/ **125** 180/ **190**	mV mV (min) mV (max)
V_{SC}	Short-Circuit Current Limit Sense Voltage	V_{IN} = 5V	343	**250** **415**	mV mV (min) mV (max)
V_{SL}	Internal Compensation Ramp Voltage	V_{IN} = 5V	92	**52** **132**	mV mV(min) mV(max)
V_{SL} ratio	V_{SL}/V_{SENSE}		0.49	0.30 0.70	(min) (max)
V_{OVP}	Output Over-voltage Protection (with respect to feedback voltage) (5)	V_{COMP} = 1.4V	50	32/ **25** 78/ **85**	mV mV(min) mV(max)

(1) The voltage on the drive pin, V_{DR} is equal to the input voltage when input voltage is less than 7.2V. V_{DR} is equal to 7.2V when the input voltage is greater than or equal to 7.2V.
(2) The limits for the maximum duty cycle can not be specified since the part does not permit less than 100% maximum duty cycle operation.
(3) For this test, the FA/SYNC/SD Pin is pulled to ground using a 40K resistor .
(4) For this test, the FA/SYNC/SD Pin is pulled to 5V using a 40K resistor.
(5) The over-voltage protection is specified with respect to the feedback voltage. This is because the over-voltage protection tracks the feedback voltage. The over-voltage thresold can be calculated by adding the feedback voltage, V_{FB} to the over-voltage protection specification.

Electrical Characteristics (continued)

Specifications in Standard type face are for T_J = 25°C, and in **bold type face** apply over the full **Operating Temperature Range**. Unless otherwise specified, V_{IN} = 12V, R_{FA} = 40kΩ

Symbol	Parameter	Conditions	Typical	Limit	Unit
$V_{OVP(HYS)}$	Output Over-Voltage Protection Hysteresis (5)	V_{COMP} = 1.4V	60	**20** **110**	mV mV(min) mV(max)
Gm	Error Ampifier Transconductance	V_{COMP} = 1.4V I_{EAO} = 100µA (Source/Sink)	800	600/ **365** 1000/ **1265**	µmho µmho (min) µmho (max)
A_{VOL}	Error Amplifier Voltage Gain	V_{COMP} = 1.4V I_{EAO} = 100µA (Source/Sink)	38	**26** **44**	V/V V/V (min) V/V (max)
I_{EAO}	Error Amplifier Output Current (Source/ Sink)	Source, V_{COMP} = 1.4V, V_{FB} = 0V	110	80/ **50** 140/ **180**	µA µA (min) µA (max)
		Sink, V_{COMP} = 1.4V, V_{FB} = 1.4V	−140	−100/ **−85** −180/ **−185**	µA µA (min) µA (max)
V_{EAO}	Error Amplifier Output Voltage Swing	Upper Limit V_{FB} = 0V COMP Pin = Floating	2.2	**1.8** **2.4**	V V(min) V(max)
		Lower Limit V_{FB} = 1.4V	0.56	**0.2** **1.0**	V V(min) V(max)
T_{SS}	Internal Soft-Start Delay	V_{FB} = 1.2V, V_{COMP} = Floating	4		msec
T_r	Drive Pin Rise Time	Cgs = 3000pf, V_{DR} = 0 to 3V	25		ns
T_f	Drive Pin Fall Time	Cgs = 3000pf, V_{DR} = 0 to 3V	25		ns
VSD	Shutdown and Synchronization signal threshold (6)	Output = High	1.27	**1.4**	V V (max)
		Output = Low	0.65	**0.3**	V V (min)
I_{SD}	Shutdown Pin Current	V_{SD} = 5V	−1		µA
		V_{SD} = 0V	+1		
I_{FB}	Feedback Pin Current		15		nA
TSD	Thermal Shutdown		165		°C
T_{sh}	Thermal Shutdown Hysteresis		10		°C
θ_{JA}	Thermal Resistance	VSSOP-8 Package	200		°C/W

(6) The FA/SYNC/SD pin should be pulled to V_{IN} through a resistor to turn the regulator off.

Typical Performance Characteristics

Unless otherwise specified, V_{IN} = 12V, T_J = 25°C.

I_Q vs Temperature & Input Voltage

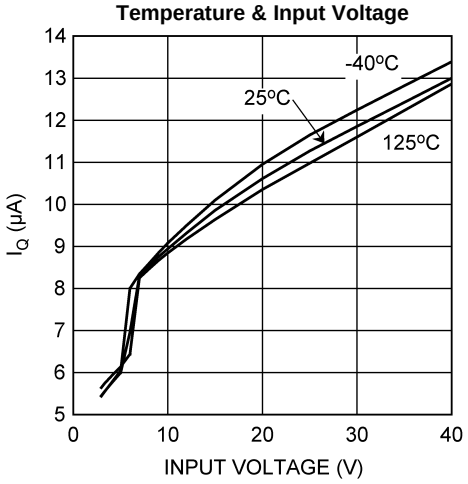


Figure 3.

I_{Supply} vs Input Voltage (Non-Switching)

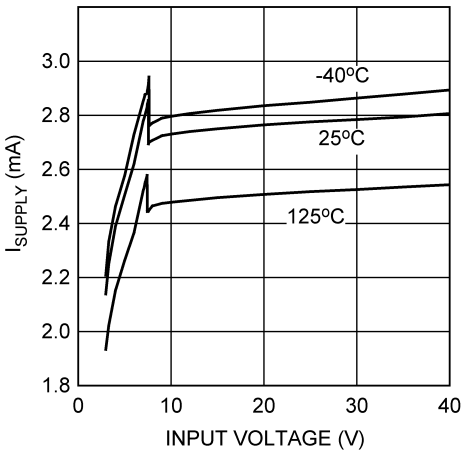


Figure 4.

I_{Supply} vs V_{IN}

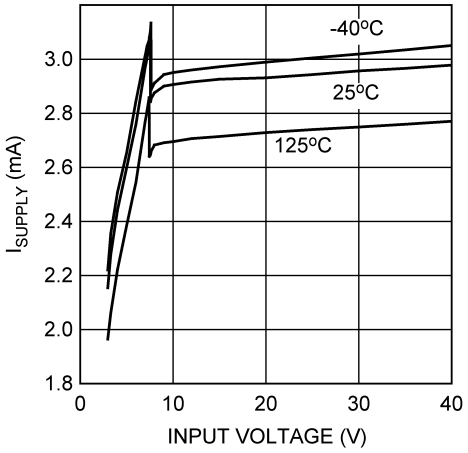


Figure 5.

Switching Frequency vs RFA

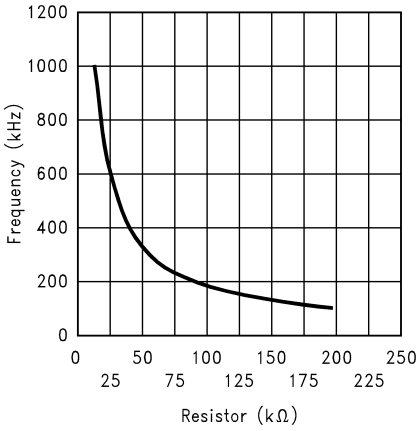


Figure 6.

Typical Performance Characteristics (continued)

Unless otherwise specified, V_{IN} = 12V, T_J = 25°C.

Frequency vs Temperature

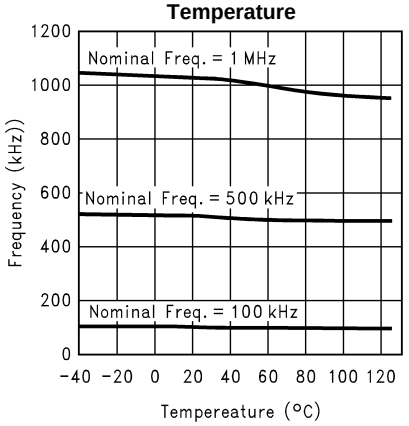


Figure 7.

Drive Voltage vs Input Voltage

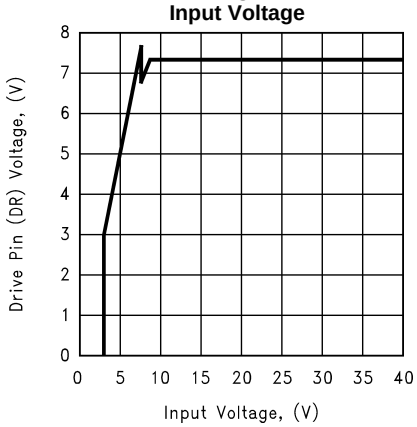


Figure 8.

Current Sense Threshold vs Input Voltage

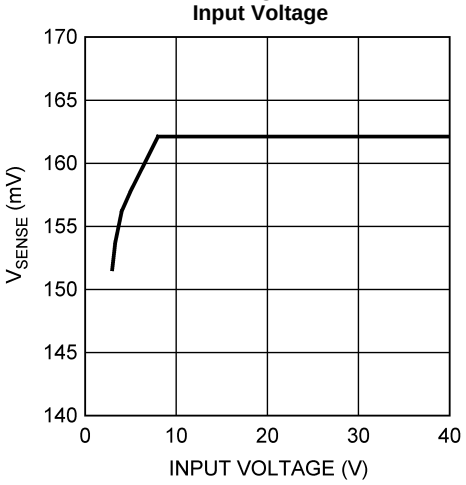


Figure 9.

COMP Pin Voltage vs Load Current

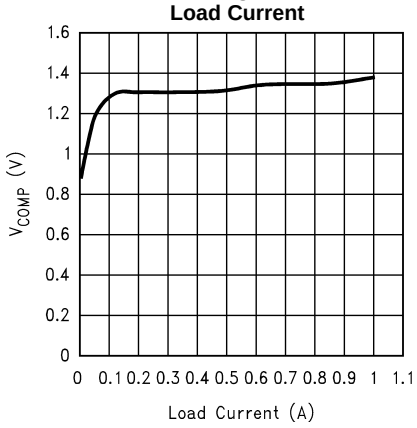


Figure 10.

Efficiency vs Load Current (3.3V In and 12V Out)

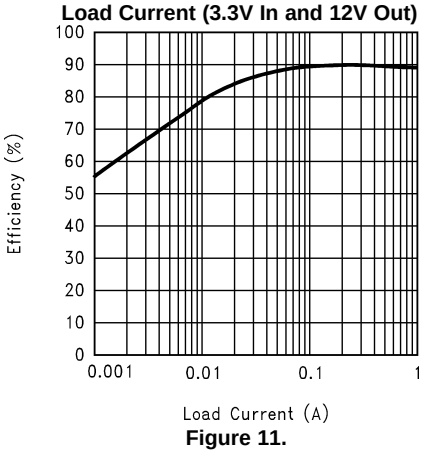


Figure 11.

Efficiency vs Load Current (5V In and 12V Out)

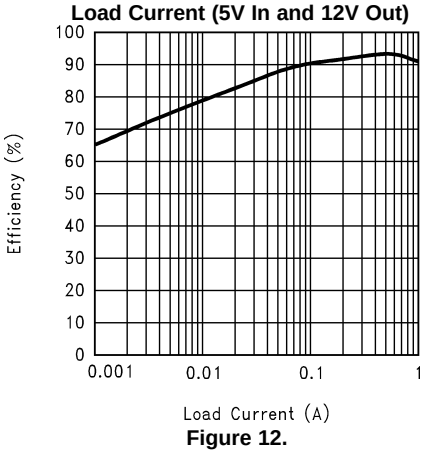


Figure 12.

Typical Performance Characteristics (continued)

Unless otherwise specified, V_{IN} = 12V, T_J = 25°C.

Efficiency vs Load Current (9V In and 12V Out)

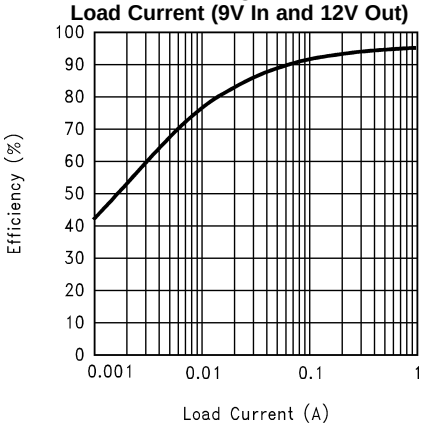


Figure 13.

Efficiency vs Load Current (3.3V In and 5V Out)

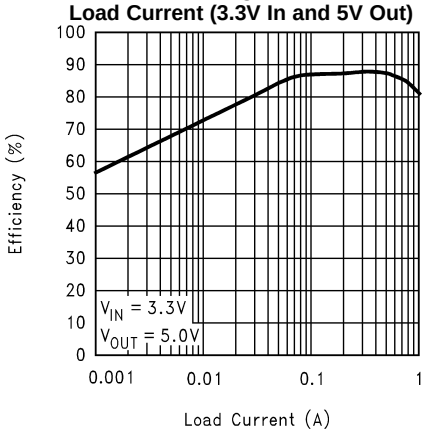


Figure 14.

Error Amplifier Gain

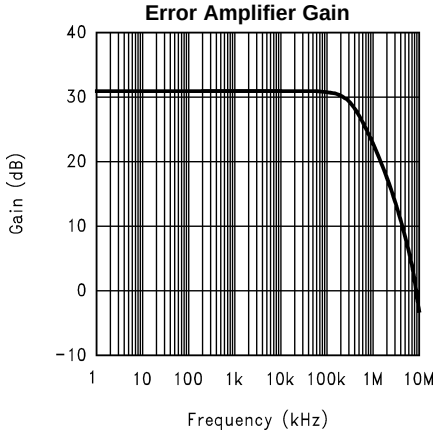


Figure 15.

Error Amplifier Phase

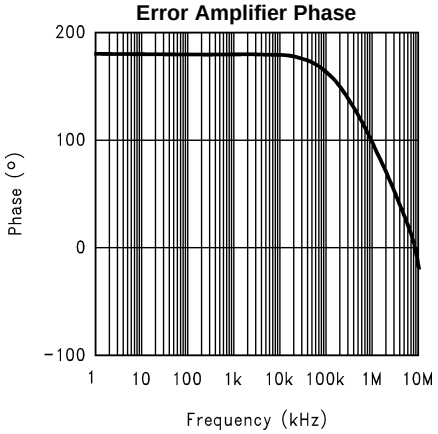


Figure 16.

COMP Pin Source Current vs Temperature

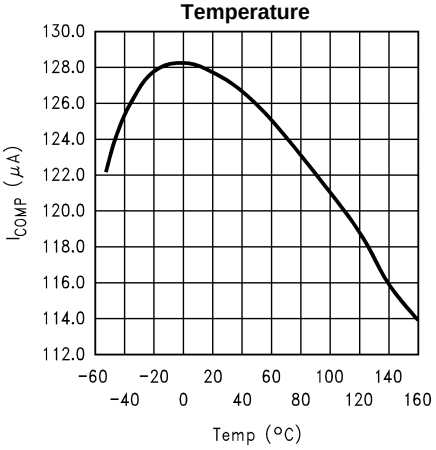


Figure 17.

Short Circuit Protection vs Input Voltage

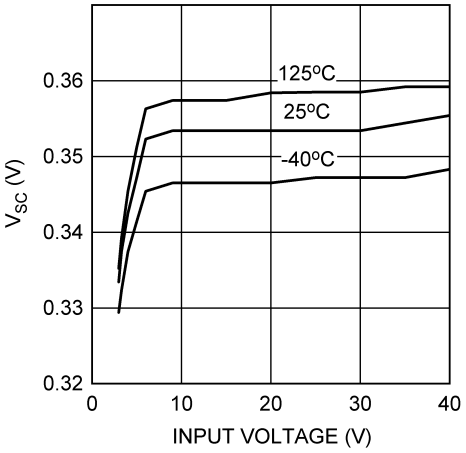


Figure 18.

Typical Performance Characteristics (continued)

Unless otherwise specified, V_{IN} = 12V, T_J = 25°C.

Compensation Ramp vs Compensation Resistor

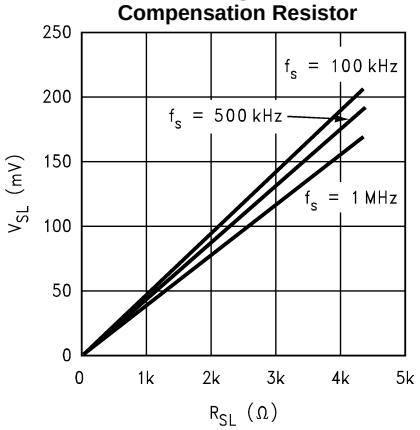


Figure 19.

Shutdown Threshold Hysteresis vs Temperature

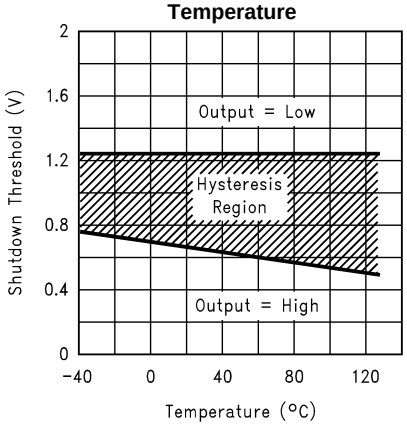


Figure 20.

Current Sense Voltage vs Duty Cycle

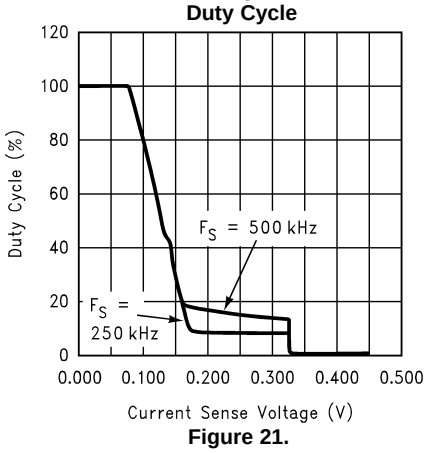
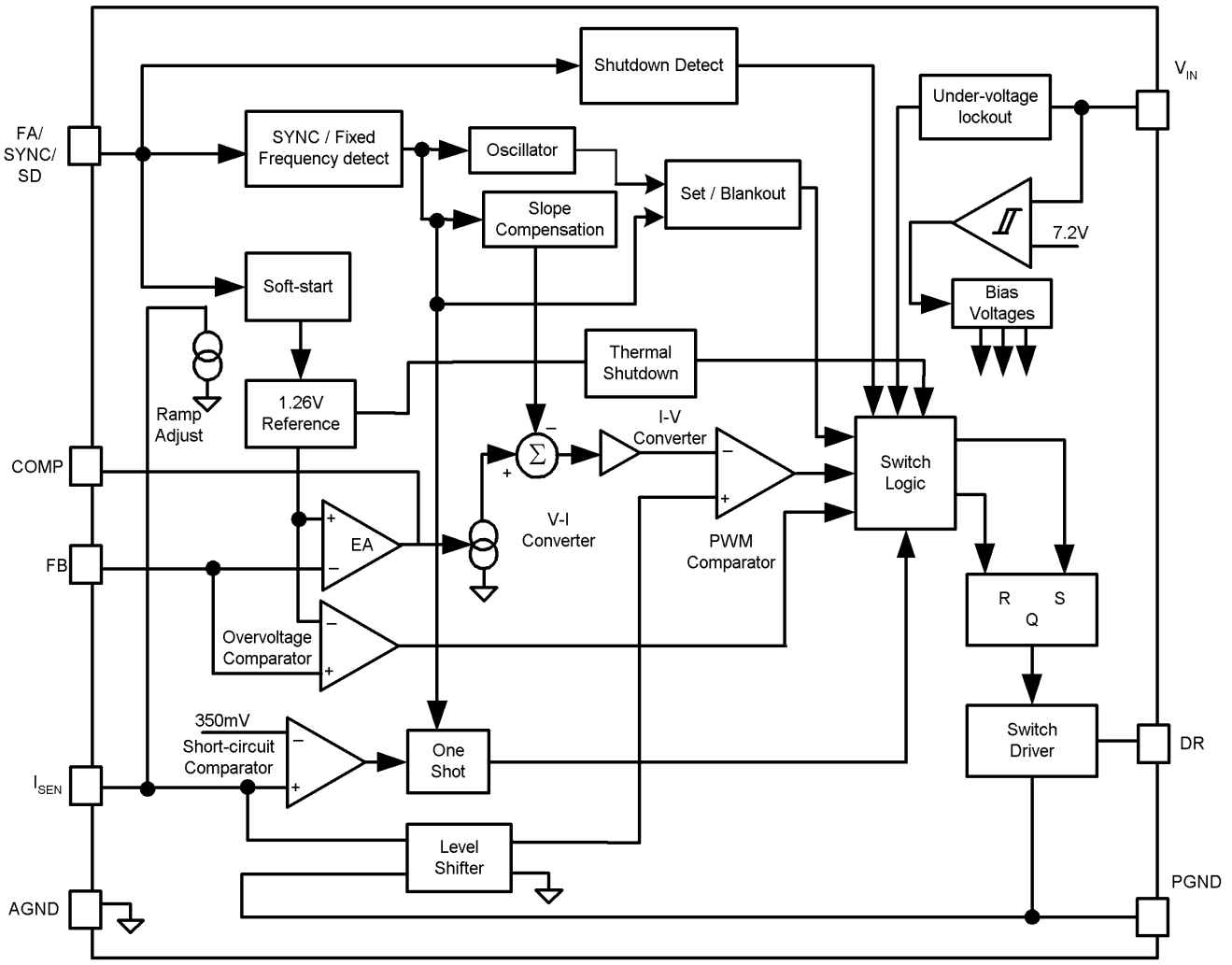


Figure 21.

FUNCTIONAL BLOCK DIAGRAM



FUNCTIONAL DESCRIPTION

The LM3488 uses a fixed frequency, Pulse Width Modulated (PWM), current mode control architecture. In a typical application circuit, the peak current through the external MOSFET is sensed through an external sense resistor. The voltage across this resistor is fed into the I_{SEN} pin. This voltage is then level shifted and fed into the positive input of the PWM comparator. The output voltage is also sensed through an external feedback resistor divider network and fed into the error amplifier negative input (feedback pin, FB). The output of the error amplifier (COMP pin) is added to the slope compensation ramp and fed into the negative input of the PWM comparator.

At the start of any switching cycle, the oscillator sets the RS latch using the SET/Blank-out and switch logic blocks. This forces a high signal on the DR pin (gate of the external MOSFET) and the external MOSFET turns on. When the voltage on the positive input of the PWM comparator exceeds the negative input, the RS latch is reset and the external MOSFET turns off.

The voltage sensed across the sense resistor generally contains spurious noise spikes, as shown in Figure 22. These spikes can force the PWM comparator to reset the RS latch prematurely. To prevent these spikes from resetting the latch, a blank-out circuit inside the IC prevents the PWM comparator from resetting the latch for a short duration after the latch is set. This duration is about 150ns and is called the blank-out time.

Under extremely light load or no-load conditions, the energy delivered to the output capacitor when the external MOSFET is on during the blank-out time is more than what is delivered to the load. An over-voltage comparator inside the LM3488 prevents the output voltage from rising under these conditions. The over-voltage comparator senses the feedback (FB pin) voltage and resets the RS latch under these conditions. The latch remains in reset state till the output decays to the nominal value.

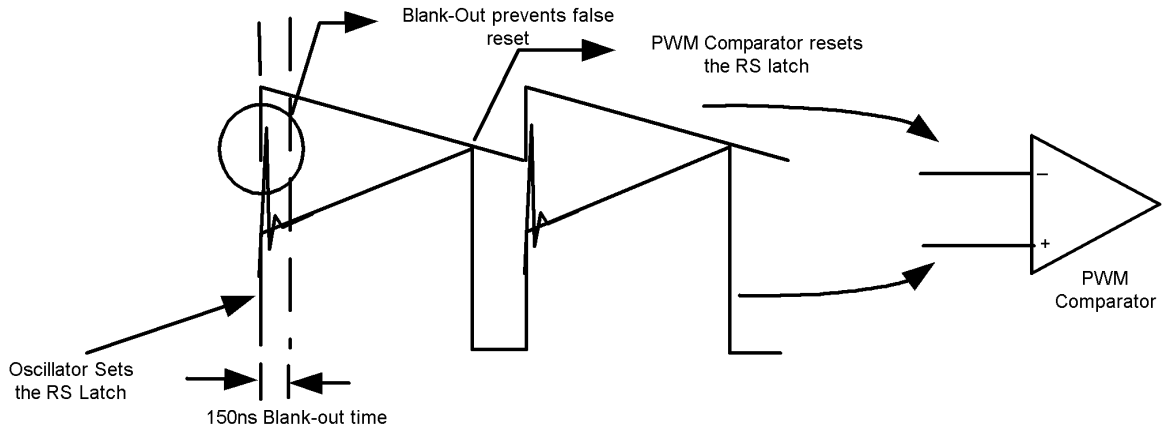


Figure 22. Basic Operation of the PWM comparator

SLOPE COMPENSATION RAMP

The LM3488 uses a current mode control scheme. The main advantages of current mode control are inherent cycle-by-cycle current limit for the switch, and simpler control loop characteristics. It is also easy to parallel power stages using current mode control since as current sharing is automatic.

Current mode control has an inherent instability for duty cycles greater than 50%, as shown in Figure 23. In Figure 23, a small increase in the load current causes the switch current to increase by ΔI_O. The effect of this load change, ΔI_1, is :

$$\Delta I_1 = -\left(\frac{M_2}{M_1}\right)\Delta I_O = -\left(\frac{D}{1-D}\right)\Delta I_O \quad (1)$$

From the above equation, when D > 0.5, ΔI_1 will be greater than ΔI_O. In other words, the disturbance is divergent. So a very small perturbation in the load will cause the disturbance to increase.

To prevent the sub-harmonic oscillations, a compensation ramp is added to the control signal, as shown in Figure 24.

With the compensation ramp,

$$\Delta I_1 = -\left(\frac{M_2 - M_C}{M_1 + M_C}\right)\Delta I_O \quad (2)$$

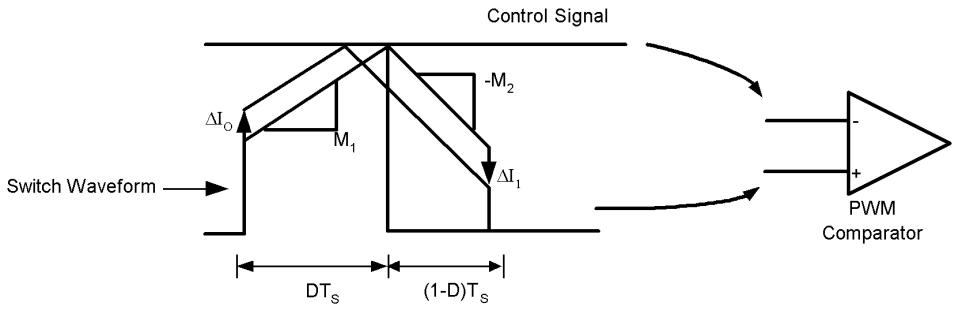


Figure 23. Sub-Harmonic Oscillation for D>0.5

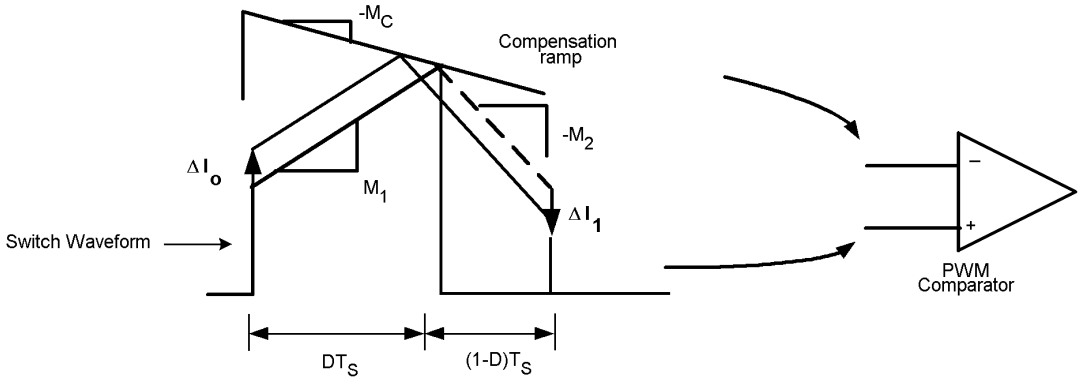


Figure 24. Compensation Ramp Avoids Sub-Harmonic Oscillation

The compensation ramp has been added internally in LM3488. The slope of this compensation ramp has been selected to satisfy most of the applications. The slope of the internal compensation ramp depends on the frequency. This slope can be calculated using the formula:

$$M_C = V_{SL}.F_S \text{ Volts/second} \quad (3)$$

In the above equation, V_{SL} is the amplitude of the internal compensation ramp. Limits for V_{SL} have been specified in the electrical characteristics.

In order to provide the user additional flexibility, a patented scheme has been implemented inside the IC to increase the slope of the compensation ramp externally, if the need arises. Adding a single external resistor, R_{SL}(as shown in Figure 25) increases the slope of the compensation ramp, M_C by :

$$\Delta M_C = \frac{40x10^{-6} \cdot R_{SL} \cdot F_S}{R_{SEN}} \frac{\text{Amps}}{\text{second}} \quad (4)$$

In this equation, ΔV_{SL} is equal to $40.10^{-6}R_{SL}$. Hence,

$$\Delta M_C = \frac{\Delta V_{SL}.F_S}{R_{SEN}} \frac{\text{Amps}}{\text{second}} \quad (5)$$

ΔV_{SL} versus R_{SL} has been plotted in Figure 26 for different frequencies.

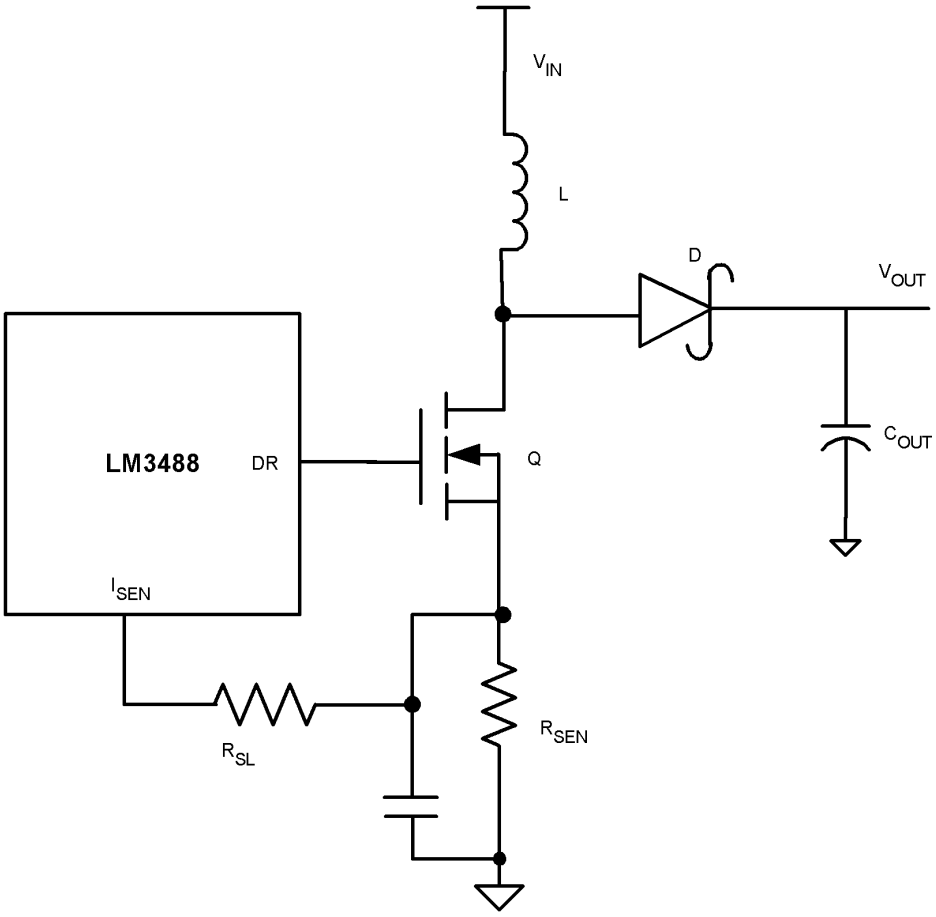


Figure 25. Increasing the Slope of the Compensation Ramp

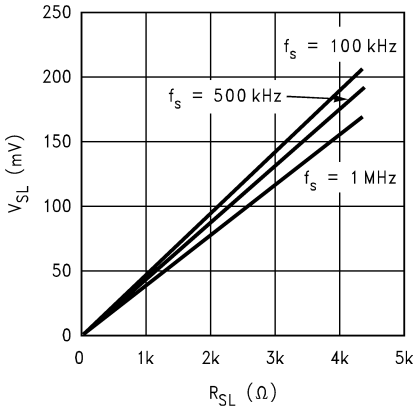


Figure 26. ΔV_{SL} vs R_{SL}

FREQUENCY ADJUST/SYNCHRONIZATION/SHUTDOWN

The switching frequency of LM3488 can be adjusted between 100kHz and 1MHz using a single external resistor. This resistor must be connected between FA/SYNC/SD pin and ground, as shown in Figure 27. See Typical Performance Characteristics to determine the value of the resistor required for a desired switching frequency.

The LM3488 can be synchronized to an external clock. The external clock must be connected to the FA/SYNC/SD pin through a resistor, R_{SYNC} as shown in Figure 28. The value of this resistor is dependent on the off time of the synchronization pulse, $T_{OFF(SYNC)}$. Table 1 shows the range of resistors to be used for a given $T_{OFF(SYNC)}$.

Table 1.

$T_{OFF(SYNC)}$ (µsec)	R_{SYNC} range (kΩ)
1	5 to 13
2	20 to 40
3	40 to 65
4	55 to 90
5	70 to 110
6	85 to 140
7	100 to 160
8	120 to 190
9	135 to 215
10	150 to 240

It is also necessary to have the width of the synchronization pulse wider than the duty cycle of the converter (when DR pin is high and the switching point is low). It is also necessary to have the synchronization pulse width ≥ 300nsecs.

The FA/SYNC/SD pin also functions as a shutdown pin. If a high signal (see Electrical Characteristics for definition of high signal) appears on the FA/SYNC/SD pin, the LM3488 stops switching and goes into a low current mode. The total supply current of the IC reduces to less than 10µA under these conditions.

Figure 29 and Figure 30 show implementation of shutdown function when operating in Frequency adjust mode and synchronization mode respectively. In frequency adjust mode, connecting the FA/SYNC/SD pin to ground forces the clock to run at a certain frequency. Pulling this pin high shuts down the IC. In frequency adjust or synchronization mode, a high signal for more than 30µs shuts down the IC.

Figure 31 shows implementation of both frequency adjust with R_{FA} resistor and frequency synchronization with R_{SYNC}. The switching frequency is defined by R_{FA} when a synchronization signal is not applied. When sync is applied it overrides the R_{FA} setting.

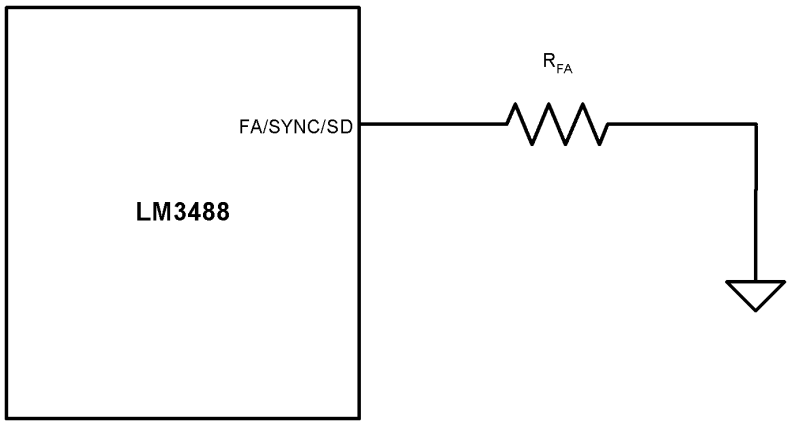


Figure 27. Frequency Adjust

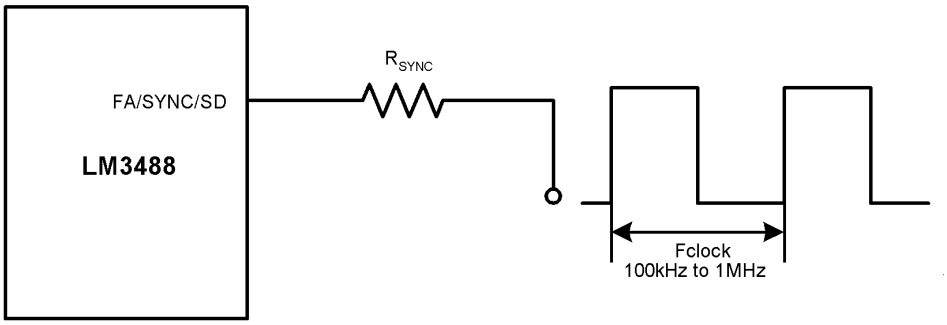


Figure 28. Frequency Synchronization

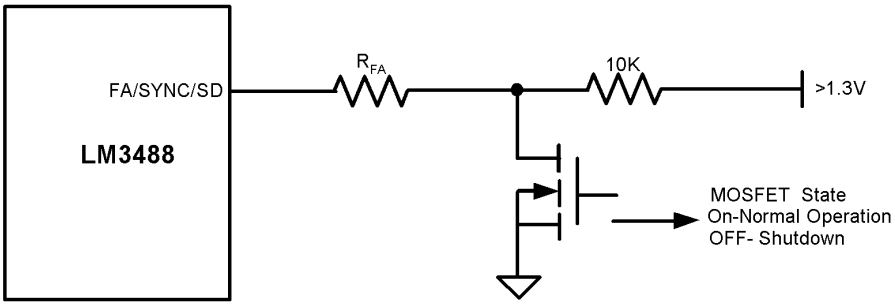


Figure 29. Shutdown Operation in Frequency Adjust Mode

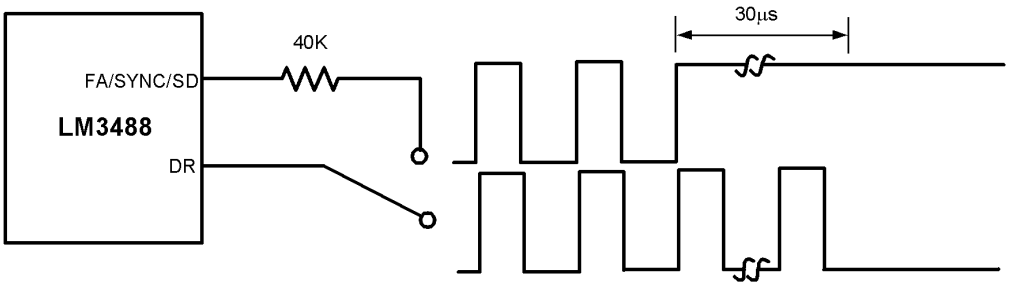


Figure 30. Shutdown Operation in Synchronization Mode

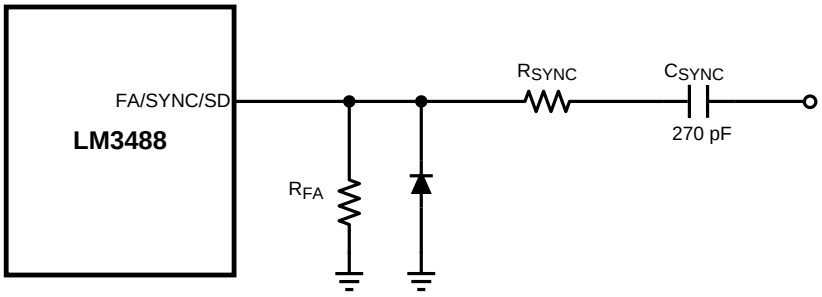


Figure 31. Frequency Adjust or Frequency Synchronization

SHORT-CIRCUIT PROTECTION

When the voltage across the sense resistor (measured on I_{SEN} Pin) exceeds 350mV, short-circuit current limit gets activated. A comparator inside LM3488 reduces the switching frequency by a factor of 5 and maintains this condition till the short is removed.

TYPICAL APPLICATIONS

The LM3488 may be operated in either continuous or discontinuous conduction mode. The following applications are designed for continuous conduction operation. This mode of operation has higher efficiency and lower EMI characteristics than the discontinuous mode.

BOOST CONVERTER

The most common topology for LM3488 is the boost or step-up topology. The boost converter converts a low input voltage into a higher output voltage. The basic configuration for a boost regulator is shown in Figure 32. In continuous conduction mode (when the inductor current never reaches zero at steady state), the boost regulator operates in two cycles. In the first cycle of operation, MOSFET Q is turned on and energy is stored in the inductor. During this cycle, diode D is reverse biased and load current is supplied by the output capacitor, C_{OUT}.

In the second cycle, MOSFET Q is off and the diode is forward biased. The energy stored in the inductor is transferred to the load and output capacitor. The ratio of these two cycles determines the output voltage. The output voltage is defined as:

$$V_{OUT} = \frac{V_{IN}}{1-D} \tag{6}$$

(ignoring the drop across the MOSFET and the diode), or

$$V_{OUT} + V_D = \frac{V_{IN} - V_Q}{1-D} \tag{7}$$

where

- D is the duty cycle of the switch
- V_D is the forward voltage drop of the diode
- V_Q is the drop across the MOSFET when it is on

The following sections describe selection of components for a boost converter.

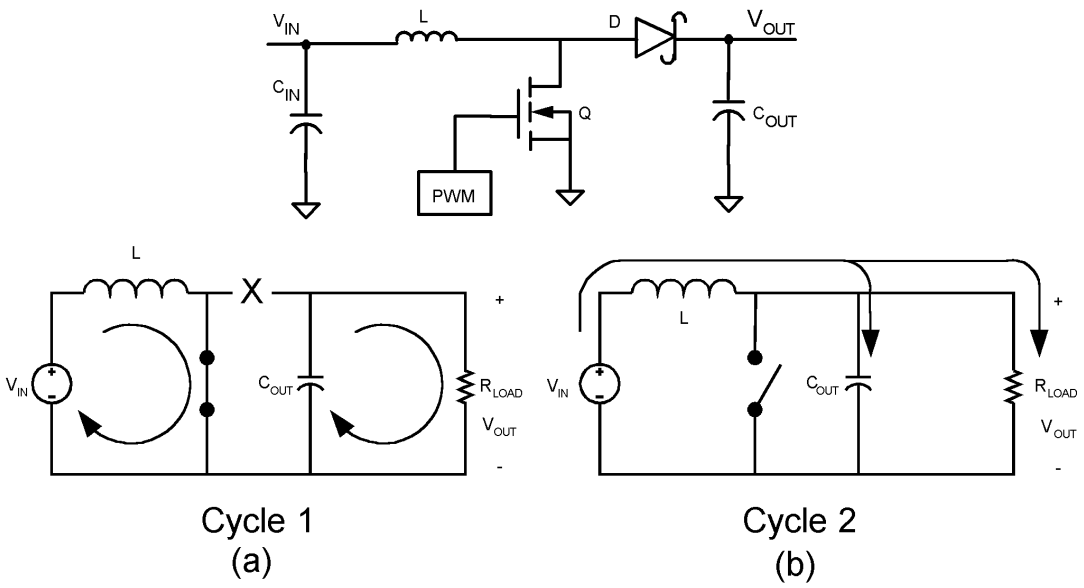


Figure 32. Simplified Boost Converter Diagram
(a) First cycle of operation
(b) Second cycle of operation

POWER INDUCTOR SELECTION

The inductor is one of the two energy storage elements in a boost converter. Figure 33 shows how the inductor current varies during a switching cycle. The current through an inductor is quantified as:

$$V_L(t) = L \frac{di_L(t)}{dt} \quad (8)$$

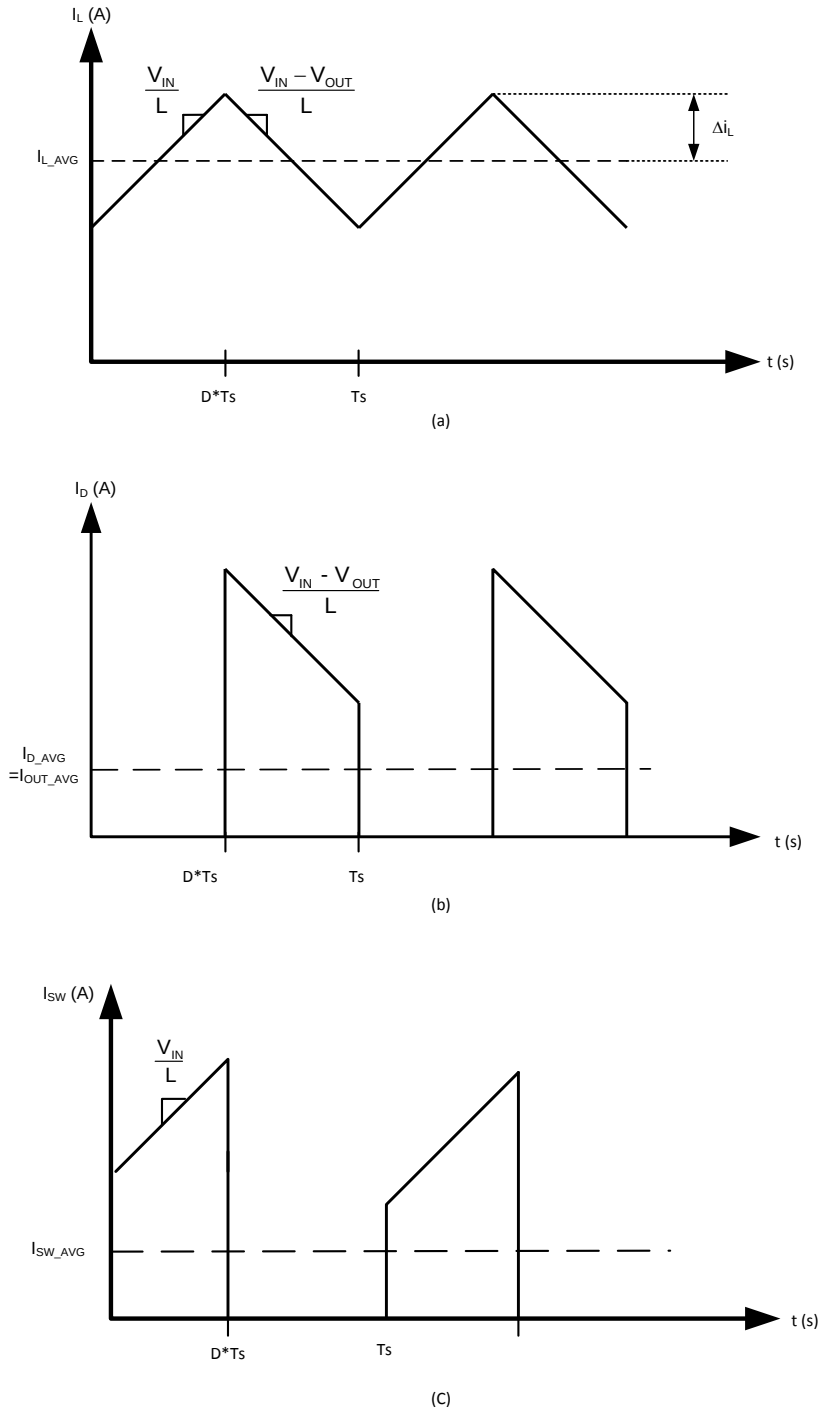


Figure 33. A. Inductor Current B. Diode Current C. Switch Current

If $V_L(t)$ is constant, $di_L(t)/dt$ must be constant. Hence, for a given input voltage and output voltage, the current in the inductor changes at a constant rate.

The important quantities in determining a proper inductance value are $\bar{I}_L$ (the average inductor current) and Δi_L (the inductor current ripple). If Δi_L is larger than $\bar{I}_L$, the inductor current will drop to zero for a portion of the cycle and the converter will operate in discontinuous conduction mode. If Δi_L is smaller than $\bar{I}_L$, the inductor current will stay above zero and the converter will operate in continuous conduction mode. All the analysis in this datasheet assumes operation in continuous conduction mode. To operate in continuous conduction mode, the following conditions must be met:

$$I_L > \Delta i_L \tag{9}$$

$$\frac{I_{OUT}}{1-D} > \frac{DV_{IN}}{2f_S L} \tag{10}$$

$$L > \frac{D(1-D)V_{IN}}{2I_{OUT}f_S} \tag{11}$$

Choose the minimum I_{OUT} to determine the minimum L. A common choice is to set Δi_L to 30% of $\bar{I}_L$. Choosing an appropriate core size for the inductor involves calculating the average and peak currents expected through the inductor. In a boost converter,

$$\bar{I}_L = \frac{I_{OUT}}{1-D} \tag{12}$$

and $I_{L\_peak} = \bar{I}_L(max) + \Delta i_L(max)$,

where

$$\Delta i_L = \frac{DV_{IN}}{2f_S L} \tag{13}$$

A core size with ratings higher than these values should be chosen. If the core is not properly rated, saturation will dramatically reduce overall efficiency.

The LM3488 can be set to switch at very high frequencies. When the switching frequency is high, the converter can be operated with very small inductor values. With a small inductor value, the peak inductor current can be extremely higher than the output currents, especially under light load conditions.

The LM3488 senses the peak current through the switch. The peak current through the switch is the same as the peak current calculated above.

PROGRAMMING THE OUTPUT VOLTAGE

The output voltage can be programmed using a resistor divider between the output and the feedback pins, as shown in Figure 34. The resistors are selected such that the voltage at the feedback pin is 1.26V. R_{F1} and R_{F2} can be selected using the equation,

$$V_{OUT} = 1.26\left(1+\frac{R_{F1}}{R_{F2}}\right) \tag{14}$$

A 100pF capacitor may be connected between the feedback and ground pins to reduce noise.

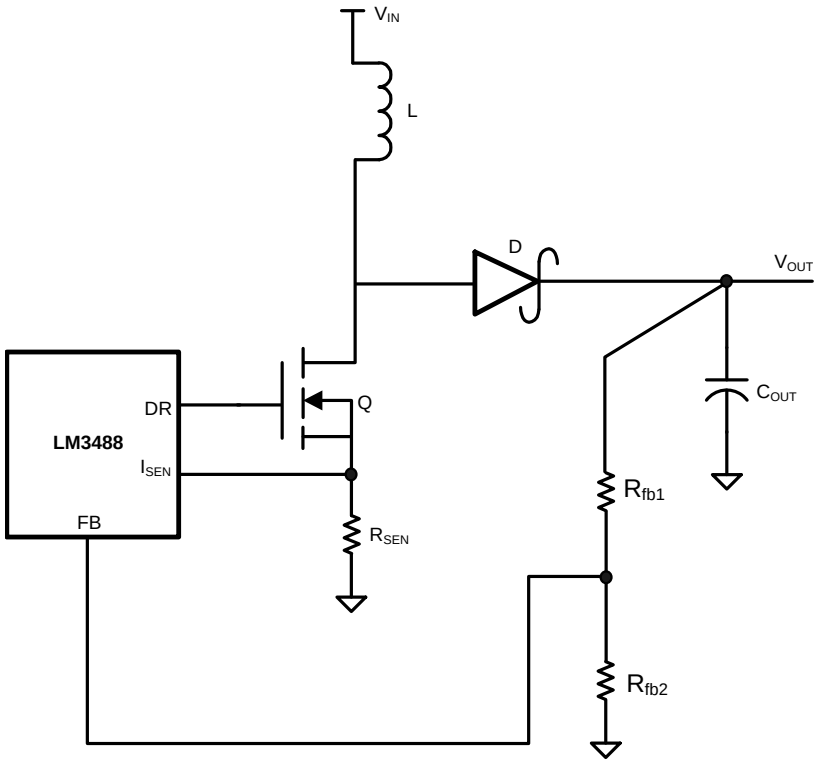


Figure 34. Adjusting the Output Voltage

SETTING THE CURRENT LIMIT

The maximum amount of current that can be delivered to the load is set by the sense resistor, R_{SEN}. Current limit occurs when the voltage that is generated across the sense resistor equals the current sense threshold voltage, V_{SENSE}. When this threshold is reached, the switch will be turned off until the next cycle. Limits for V_{SENSE} are specified in Electrical Characteristics. V_{SENSE} represents the maximum value of the internal control signal V_{CS}. This control signal, however, is not a constant value and changes over the course of a period as a result of the internal compensation ramp (see Figure 22). Therefore the current limit threshold will also change. The actual current limit threshold is a function of the sense voltage (V_{SENSE}) and the internal compensation ramp:

$$R_{SEN} \times ISW_{LIMIT} = VCS_{MAX} = V_{SENSE} - (D \times V_{SL})$$

where

- ISW_{LIMIT} is the peak switch current limit, defined by the equation below. As duty cycle increases, the control voltage is reduced as V_{SL} ramps up. Since current limit threshold varies with duty cycle, the following equation should be used to select R_{SEN} and set the desired current limit threshold: (15)

$$R_{SEN} = \frac{V_{SENSE} - (D \times V_{SL})}{ISW_{LIMIT}} \quad (16)$$

The numerator of the above equation is V_{CS}, and ISW_{LIMIT} is calculated as:

$$ISW_{LIMIT} = \left[\frac{I_{OUT}}{(1-D)} + \frac{(D \times V_{IN})}{(2 \times f_S \times L)}\right] \quad (17)$$

To avoid false triggering, the current limit value should have some margin above the maximum operating value, typically 120%. Values for both V_{SENSE} and V_{SL} are specified in Electrical Characteristics. However, calculating with the limits of these two specs could result in an unrealistically wide current limit or R_{SEN} range. Therefore, the following equation is recommended, using the V_{SL} ratio value given in Electrical Characteristics:

$$R_{SEN} = \frac{V_{SENSE} - (D \times V_{SENSE} \times V_{SL}ratio)}{ISW_{LIMIT}} \quad (18)$$

R_{SEN} is part of the current mode control loop and has some influence on control loop stability. Therefore, once the current limit threshold is set, loop stability must be verified. To verify stability, use the following equation:

$$R_{SEN} < \frac{2 \times V_{SL} \times f_S \times L}{Vo - (2 \times V_{IN})} \quad (19)$$

If the selected R_{SEN} is greater than this value, additional slope compensation must be added to ensure stability, as described in CURRENT LIMIT WITH EXTERNAL SLOPE COMPENSATION.

CURRENT LIMIT WITH EXTERNAL SLOPE COMPENSATION

R_{SL} is used to add additional slope compensation when required. It is not necessary in most designs and R_{SL} should be no larger than necessary. Select R_{SL} according to the following equation:

$$R_{SL} > \frac{\frac{R_{SEN} \times (Vo - 2V_{IN})}{2 \times f_S \times L} - V_{SL}}{40\ \mu A}$$

where

- R_{SEN} is the selected value based on current limit. With R_{SL} installed, the control signal includes additional external slope to stabilize the loop, which will also have an effect on the current limit threshold. Therefore, the current limit threshold must be re-verified, as illustrated in the equations below : (20)

$$V_{CS} = V_{SENSE} - (D \times (V_{SL} + \Delta V_{SL}))$$

where

- ΔV_{SL} is the additional slope compensation generated and calculated as: (21)

$$\Delta V_{SL} = 40\ \mu A \times R_{SL} \quad (22)$$

This changes the equation for current limit (or R_{SEN}) to:

$$ISW_{LIMIT} = \frac{V_{SENSE} - (D \times (V_{SL} + \Delta V_{SL}))}{R_{SEN}} \quad (23)$$

The R_{SEN} and R_{SL} values may have to be calculated iteratively in order to achieve both the desired current limit and stable operation. In some designs R_{SL} can also help to filter noise on the ISEN pin.

If the inductor is selected such that ripple current is the recommended 30% value, and the current limit threshold is 120% of the maximum peak, a simpler method can be used to determine R_{SEN}. The equation below will provide optimum stability without RSL, provided that the above 2 conditions are met:

$$R_{SEN} = \frac{V_{SENSE}}{ISW_{LIMIT} + \left(\frac{Vo - Vi}{L \times f_S}\right) \times D} \quad (24)$$

POWER DIODE SELECTION

Observation of the boost converter circuit shows that the average current through the diode is the average load current, and the peak current through the diode is the peak current through the inductor. The diode should be rated to handle more than its peak current. The peak diode current can be calculated using the formula:

$$I_{D(Peak)} = I_{OUT} / (1-D) + \Delta I_L \quad (25)$$

In the above equation, I_{OUT} is the output current and ΔI_L has been defined in Figure 33.

The peak reverse voltage for boost converter is equal to the regulator output voltage. The diode must be capable of handling this voltage. To improve efficiency, a low forward drop schottky diode is recommended.

POWER MOSFET SELECTION

The drive pin of LM3488 must be connected to the gate of an external MOSFET. In a boost topology, the drain of the external N-Channel MOSFET is connected to the inductor and the source is connected to the ground. The drive pin (DR) voltage depends on the input voltage (see Typical Performance Characteristics). In most applications, a logic level MOSFET can be used. For very low input voltages, a sub-logic level MOSFET should be used.

The selected MOSFET directly controls the efficiency. The critical parameters for selection of a MOSFET are:

1. Minimum threshold voltage, V_{TH}(MIN)
2. On-resistance, R_{DS}(ON)
3. Total gate charge, Q_g
4. Reverse transfer capacitance, C_{RSS}
5. Maximum drain to source voltage, $V_{DS(MAX)}$

The off-state voltage of the MOSFET is approximately equal to the output voltage. $V_{DS(MAX)}$ of the MOSFET must be greater than the output voltage. The power losses in the MOSFET can be categorized into conduction losses and ac switching or transition losses. $R_{DS(ON)}$ is needed to estimate the conduction losses. The conduction loss, P_{COND}, is the I^2R loss across the MOSFET. The maximum conduction loss is given by:

$$P_{COND(MAX)} = \left[\left(\frac{I_{OUT}}{1-D_{MAX}}\right)^2 + \left(\frac{\Delta I}{3}\right)^2\right] D_{MAX} R_{DS(ON)} \quad (26)$$

where

- D_{MAX} is the maximum duty cycle.

$$D_{MAX} = \left(1 - \frac{V_{IN\,(MIN)}}{V_{OUT}}\right) \quad (27)$$

The turn-on and turn-off transitions of a MOSFET require times of tens of nano-seconds. C_{RSS} and Q_g are needed to estimate the large instantaneous power loss that occurs during these transitions.

The amount of gate current required to turn the MOSFET on can be calculated using the formula:

$$I_G = Q_g.F_S \quad (28)$$

The required gate drive power to turn the MOSFET on is equal to the switching frequency times the energy required to deliver the charge to bring the gate charge voltage to V_{DR} (see Electrical Characteristics and Typical Performance Characteristics for the drive voltage specification).

$$P_{Drive} = F_S.Q_g.V_{DR} \quad (29)$$

INPUT CAPACITOR SELECTION

Due to the presence of an inductor at the input of a boost converter, the input current waveform is continuous and triangular, as shown in Figure 33. The inductor ensures that the input capacitor sees fairly low ripple currents. However, as the input capacitor gets smaller, the input ripple goes up. The rms current in the input capacitor is given by:

$$I_{CIN(RMS)} = \Delta i_L / \sqrt{3} = \frac{1}{2\sqrt{3}}\left(\frac{V_{OUT} - V_{IN}}{V_{OUT} L f_S}\right) \quad (30)$$

The input capacitor should be capable of handling the rms current. Although the input capacitor is not as critical in a boost application, low values can cause impedance interactions. Therefore a good quality capacitor should be chosen in the range of 10µF to 20µF. If a value lower than 10µF is used, then problems with impedance interactions or switching noise can affect the LM3478. To improve performance, especially with V_{IN} below 8 volts, it is recommended to use a 20Ω resistor at the input to provide a RC filter. The resistor is placed in series with the V_{IN} pin with only a bypass capacitor attached to the V_{IN} pin directly (see Figure 35). A 0.1µF or 1µF ceramic capacitor is necessary in this configuration. The bulk input capacitor and inductor will connect on the other side of the resistor with the input power supply.

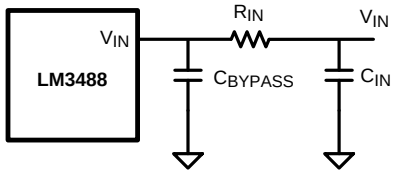


Figure 35. Reducing IC Input Noise

OUTPUT CAPACITOR SELECTION

The output capacitor in a boost converter provides all the output current when the inductor is charging. As a result it sees very large ripple currents. The output capacitor should be capable of handling the maximum rms current. The rms current in the output capacitor is:

$$I_{COUT(RMS)} = \sqrt{(1-D)\left[I_{OUT}^2 \frac{D}{(1-D)^2} + \frac{\Delta i_L^2}{3}\right]} \quad (31)$$

Where

$$\Delta i_L = \frac{DV_{IN}}{2Lf_S} \quad (32)$$

and D, the duty cycle is equal to $(V_{OUT} - V_{IN})/V_{OUT}$.

The ESR and ESL of the output capacitor directly control the output ripple. Use capacitors with low ESR and ESL at the output for high efficiency and low ripple voltage. Surface Mount tantalums, surface mount polymer electrolytic and polymer tantalum, Sanyo- OSCON, or multi-layer ceramic capacitors are recommended at the output.

DESIGNING SEPIC USING LM3488

Since the LM3488 controls a low-side N-Channel MOSFET, it can also be used in SEPIC (Single Ended Primary Inductance Converter) applications. An example of SEPIC using LM3488 is shown in Figure 36. As shown in Figure 36, the output voltage can be higher or lower than the input voltage. The SEPIC uses two inductors to step-up or step-down the input voltage. The inductors L1 and L2 can be two discrete inductors or two windings of a coupled transformer since equal voltages are applied across the inductor throughout the switching cycle. Using two discrete inductors allows use of catalog magnetics, as opposed to a custom transformer. The input ripple can be reduced along with size by using the coupled windings of transformer for L1 and L2.

Due to the presence of the inductor L1 at the input, the SEPIC inherits all the benefits of a boost converter. One main advantage of SEPIC over boost converter is the inherent input to output isolation. The capacitor CS isolates the input from the output and provides protection against shorted or malfunctioning load. Hence, the A SEPIC is useful for replacing boost circuits when true shutdown is required. This means that the output voltage falls to 0V when the switch is turned off. In a boost converter, the output can only fall to the input voltage minus a diode drop.

The duty cycle of a SEPIC is given by:

$$D = \frac{V_{OUT} + V_{DIODE}}{V_{OUT} + V_{IN} - V_Q + V_{DIODE}} \quad (33)$$

In the above equation, V_Q is the on-state voltage of the MOSFET, Q, and V_{DIODE} is the forward voltage drop of the diode.

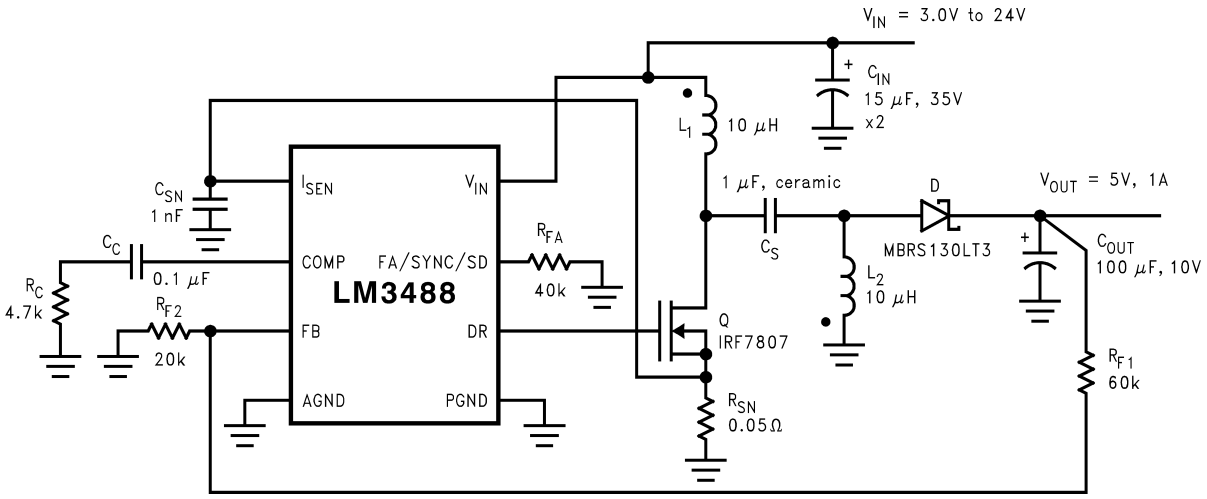


Figure 36. Typical SEPIC Converter

POWER MOSFET SELECTION

As in boost converter, the parameters governing the selection of the MOSFET are the minimum threshold voltage, $V_{TH(MIN)}$, the on-resistance, $R_{DS(ON)}$, the total gate charge, Q_g, the reverse transfer capacitance, C_{RSS}, and the maximum drain to source voltage, $V_{DS(MAX)}$. The peak switch voltage in a SEPIC is given by:

$$V_{SW(PEAK)} = V_{IN} + V_{OUT} + V_{DIODE} \quad (34)$$

The selected MOSFET should satisfy the condition:

$$V_{DS(MAX)} > V_{SW(PEAK)} \quad (35)$$

The peak switch current is given by:

$$I_{SW(PEAK)} = I_{L1(AVG)} + I_{OUT} + \frac{\Delta I_{L1} + \Delta I_{L2}}{2} \quad (36)$$

The rms current through the switch is given by:

$$I_{SWRMS} = \sqrt{\left[I_{SWPEAK}^2 - I_{SWPEAK}\left(\Delta I_{L1} + \Delta I_{L2}\right) + \frac{\left(\Delta I_{L1} + \Delta I_{L2}\right)^2}{3}\right] D} \quad (37)$$

POWER DIODE SELECTION

The Power diode must be selected to handle the peak current and the peak reverse voltage. In a SEPIC, the diode peak current is the same as the switch peak current. The off-state voltage or peak reverse voltage of the diode is $V_{IN} + V_{OUT}$. Similar to the boost converter, the average diode current is equal to the output current. Schottky diodes are recommended.

SELECTION OF INDUCTORS L1 AND L2

Proper selection of the inductors L1 and L2 to maintain constant current mode requires calculations of the following parameters.

Average current in the inductors:

$$I_{L1AVE} = \frac{DI_{OUT}}{1-D} \quad (38)$$

$$I_{L2AVE} = I_{OUT} \quad (39)$$

Peak to peak ripple current, to calculate core loss if necessary:

$$\Delta I_{L1} = \frac{(V_{IN} - V_Q)\, D}{(L1) f_S} \quad (40)$$

$$\Delta I_{L2} = \frac{(V_{IN} - V_Q)\, D}{(L2) f_S} \quad (41)$$

maintains the condition $I_L > \Delta i_L/2$ to ensure constant current mode.

$$L1 > \frac{(V_{IN} - V_Q)(1-D)}{2 I_{OUT} f_S} \quad (42)$$

$$L2 > \frac{(V_{IN} - V_Q) D}{2 I_{OUT} f_S} \quad (43)$$

Peak current in the inductor, to ensure the inductor does not saturate:

$$I_{L1PK} = \frac{D I_{OUT}}{1-D} + \frac{\Delta I_{L1}}{2} \quad (44)$$

$$I_{L2PK} = I_{OUT} + \frac{\Delta I_{L2}}{2} \quad (45)$$

I_{L1PK} must be lower than the maximum current rating set by the current sense resistor.

The value of L1 can be increased above the minimum recommended to reduce input ripple and output ripple. However, once D_{IL1} is less than 20% of I_{L1AVE}, the benefit to output ripple is minimal.

By increasing the value of L2 above the minimum recommended, Δ_{IL2} can be reduced, which in turn will reduce the output ripple voltage:

$$\Delta V_{OUT} = \left(\frac{I_{OUT}}{1-D} + \frac{\Delta I_{L2}}{2} \right) \text{ESR}$$

where

- ESR is the effective series resistance of the output capacitor. (46)

If L1 and L2 are wound on the same core, then L1 = L2 = L. All the equations above will hold true if the inductance is replaced by 2L. A good choice for transformer with equal turns is Coiltronics CTX series Octopack.

SENSE RESISTOR SELECTION

The peak current through the switch, $I_{SW(PEAK)}$ can be adjusted using the current sense resistor, R_{SEN}, to provide a certain output current. Resistor R_{SEN} can be selected using the formula:

$$R_{SEN} = \frac{V_{SENSE} - D(V_{SL} + \Delta V_{SL})}{I_{SWPEAK}} \quad (47)$$

Sepic Capacitor Selection

The selection of SEPIC capacitor, CS, depends on the rms current. The rms current of the SEPIC capacitor is given by:

$$I_{CSRMS} = \sqrt{I_{SWRMS}^2 + \left(I_{L1PK}^2 - I_{L1PK} \Delta I_{L1} + \Delta I_{L1}^2 \right)(1-D)} \quad (48)$$

The SEPIC capacitor must be rated for a large ACrms current relative to the output power. This property makes the SEPIC much better suited to lower power applications where the rms current through the capacitor is relatively small (relative to capacitor technology). The voltage rating of the SEPIC capacitor must be greater than the maximum input voltage. Tantalum capacitors are the best choice for SMT, having high rms current ratings relative to size. Ceramic capacitors could be used, but the low C values will tend to cause larger changes in voltage across the capacitor due to the large currents. High C value ceramics are expensive. Electrolytics work well for through hole applications where the size required to meet the rms current rating can be accommodated. There is an energy balance between CS and L1, which can be used to determine the value of the capacitor. The basic energy balance equation is:

$$\frac{1}{2} C_S \Delta V_S^2 = \frac{1}{2} L_1 \Delta I_{L1}^2 \quad (49)$$

Where

$$\Delta V_S = \left(\frac{V_{OUT}}{V_{OUT} + V_{IN} - V_Q + V_{DIODE}} \right) \frac{I_{OUT}}{f_S C_S} \quad (50)$$

is the ripple voltage across the SEPIC capacitor, and

$$\Delta I_{L1} = \frac{(V_{IN} - V_Q)\, D}{L_1 f_S} \quad (51)$$

is the ripple current through the inductor L1. The energy balance equation can be solved to provide a minimum value for C_S:

$$C_S \geq L_1 \frac{I_{OUT}^2}{(V_{IN} - V_Q)^2} \quad (52)$$

Input Capacitor Selection

Similar to a boost converter, the SEPIC has an inductor at the input. Hence, the input current waveform is continuous and triangular. The inductor ensures that the input capacitor sees fairly low ripple currents. However, as the input capacitor gets smaller, the input ripple goes up. The rms current in the input capacitor is given by:

$$I_{CIN(RMS)} = \Delta I_{L1} / \sqrt{12} = \frac{D}{2\sqrt{3}} \left(\frac{V_{IN} - V_Q}{L_1 f_S} \right) \quad (53)$$

The input capacitor should be capable of handling the rms current. Although the input capacitor is not as critical in a boost application, low values can cause impedance interactions. Therefore a good quality capacitor should be chosen in the range of 10µF to 20µF. If a value lower than 10µF is used, then problems with impedance interactions or switching noise can affect the LM3478. To improve performance, especially with V_{IN} below 8 volts, it is recommended to use a 20Ω resistor at the input to provide a RC filter. The resistor is placed in series with the V_{IN} pin with only a bypass capacitor attached to the V_{IN} pin directly (see Figure 35). A 0.1µF or 1µF ceramic capacitor is necessary in this configuration. The bulk input capacitor and inductor will connect on the other side of the resistor with the input power supply.

Output Capacitor Selection

The ESR and ESL of the output capacitor directly control the output ripple. Use low capacitors with low ESR and ESL at the output for high efficiency and low ripple voltage. Surface mount tantalums, surface mount polymer electrolytic and polymer tantalum, Sanyo- OSCON, or multi-layer ceramic capacitors are recommended at the output.

The output capacitor of the SEPIC sees very large ripple currents (similar to the output capacitor of a boost converter. The rms current through the output capacitor is given by:

$$I_{RMS} = \sqrt{\left[I_{SWPK}^2 - I_{SWPK} (\Delta I_{L1} + \Delta I_{L2}) + \frac{(\Delta I_{L1} + \Delta I_{L2})^2}{3} \right] (1\text{-}D) - I_{OUT}^2} \quad (54)$$

The ESR and ESL of the output capacitor directly control the output ripple. Use low capacitors with low ESR and ESL at the output for high efficiency and low ripple voltage. Surface mount tantalums, surface mount polymer electrolytic and polymer tantalum, Sanyo- OSCON, or multi-layer ceramic capacitors are recommended at the output for low ripple.

Other Application Circuits

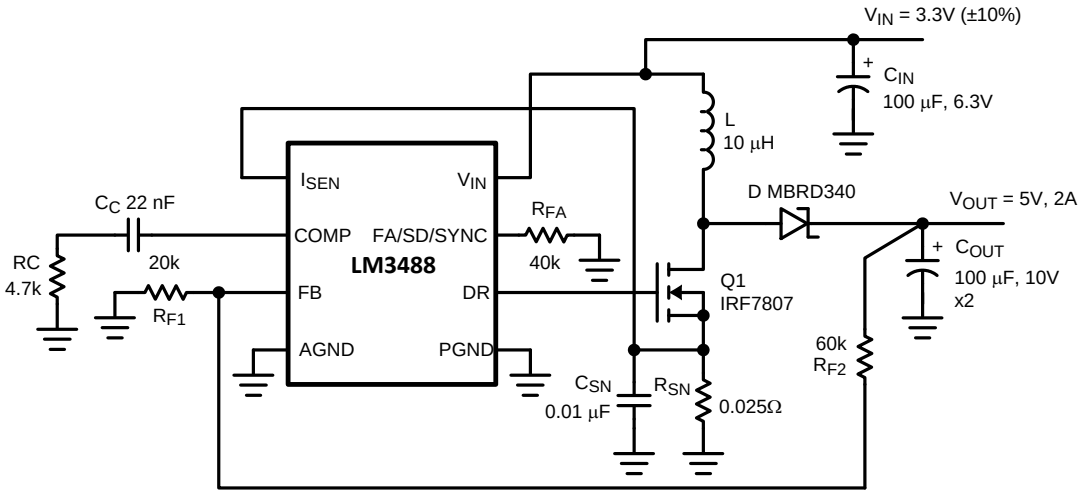


Figure 37. Typical High Efficiency Step-Up (Boost) Converter

REVISION HISTORY

Changes from Revision L (March 2013) to Revision M	Page
• Changed layout of National Data Sheet to TI format	26

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
LM3488MM	ACTIVE	VSSOP	DGK	8	1000	TBD	Call TI	Call TI		S21B	Samples
LM3488MM/NOPB	ACTIVE	VSSOP	DGK	8	1000	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	-40 to 125	S21B	Samples
LM3488MMX	NRND	VSSOP	DGK	8	3500	TBD	Call TI	Call TI	-40 to 125	S21B	
LM3488MMX/NOPB	ACTIVE	VSSOP	DGK	8	3500	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	-40 to 125	S21B	Samples
LM3488QMM/NOPB	ACTIVE	VSSOP	DGK	8	1000	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	-40 to 125	SSKB	Samples
LM3488QMMX/NOPB	ACTIVE	VSSOP	DGK	8	3500	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	-40 to 125	SSKB	Samples

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

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

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

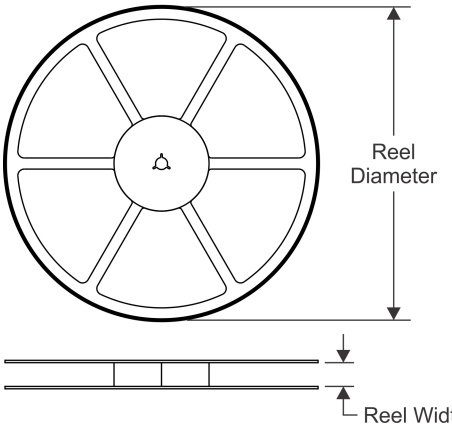
(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

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

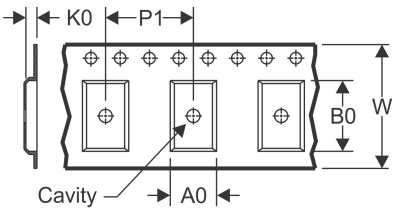
(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

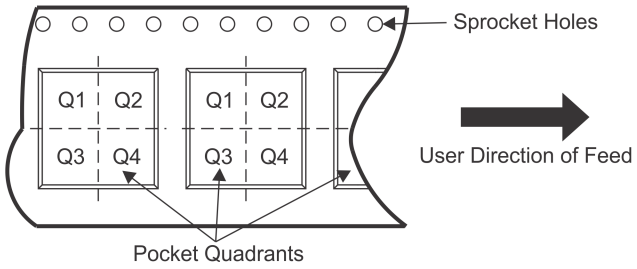


TAPE DIMENSIONS



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

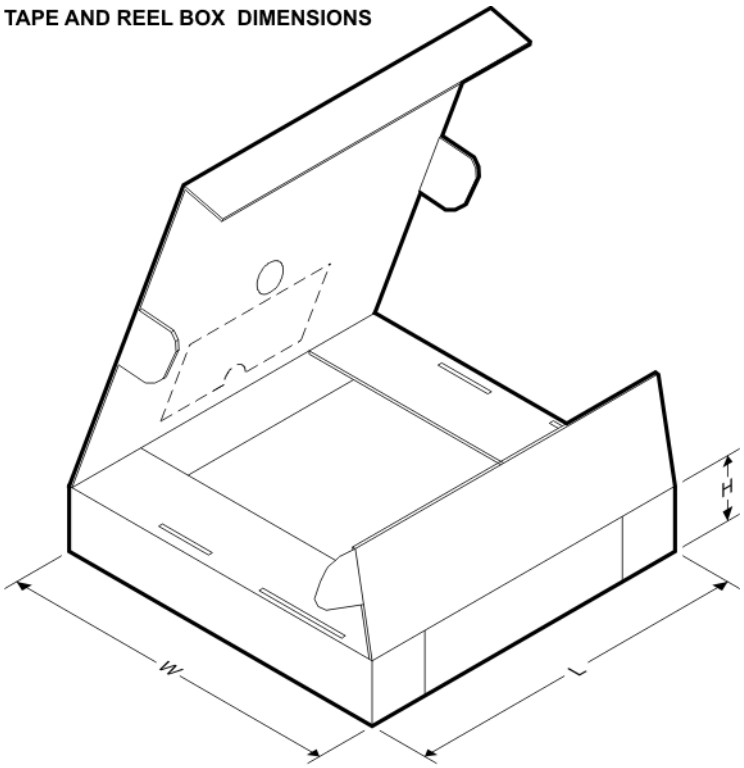
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
LM3488MM	VSSOP	DGK	8	1000	178.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
LM3488MM/NOPB	VSSOP	DGK	8	1000	178.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
LM3488MMX	VSSOP	DGK	8	3500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
LM3488MMX/NOPB	VSSOP	DGK	8	3500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
LM3488QMM/NOPB	VSSOP	DGK	8	1000	178.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
LM3488QMMX/NOPB	VSSOP	DGK	8	3500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1

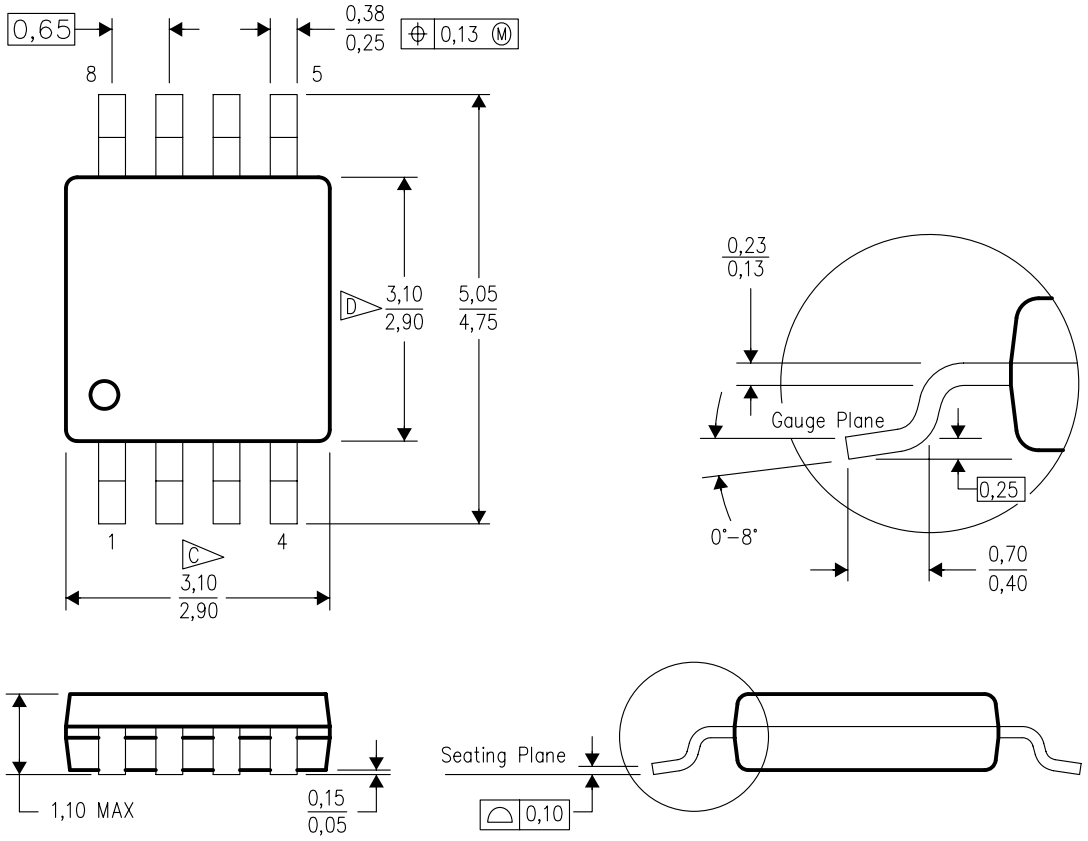
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
LM3488MM	VSSOP	DGK	8	1000	210.0	185.0	35.0
LM3488MM/NOPB	VSSOP	DGK	8	1000	210.0	185.0	35.0
LM3488MMX	VSSOP	DGK	8	3500	367.0	367.0	35.0
LM3488MMX/NOPB	VSSOP	DGK	8	3500	367.0	367.0	35.0
LM3488QMM/NOPB	VSSOP	DGK	8	1000	210.0	185.0	35.0
LM3488QMMX/NOPB	VSSOP	DGK	8	3500	367.0	367.0	35.0

DGK (S–PDSO–G8) PLASTIC SMALL–OUTLINE PACKAGE



4073329/E 05/06

NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 per end.
D. Body width does not include interlead flash. Interlead flash shall not exceed 0.50 per side.
E. Falls within JEDEC MO–187 variation AA, except interlead flash.

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