

## Wide Input Voltage, Adjustable Frequency, 2 Amp Non-Synchronous Buck Regulator with Enable and NPOR

### FEATURES AND BENEFITS

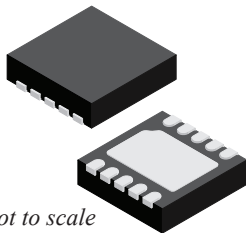
- Automotive AEC-Q100 qualified
- Supply voltage from 3.8 to 36 V
- Output voltage adjustable from 0.8 to 30 V
- Maximized duty cycle for low-dropout operation
- Low 30  $\mu$ A operational quiescent current
- 150 m $\Omega$  integrated MOSFET switch
- Programmable switching frequency up to 4 MHz
- Improved EMC with frequency dithering and controlled switch-node rise and fall times
- Active-low power-on reset signal (NPOR)
- Ceramic capacitor stable
- Internal soft-start
- Overcurrent protection

### APPLICATIONS

- High-voltage power conversion
- Automotive systems
- Industrial power systems
- Distributed power systems
- Battery-powered systems

### PACKAGES:

10-Pin DFN with Exposed Thermal Pad (suffix EJ)



Not to scale

### DESCRIPTION

The A8587 is a high-frequency step-down switching regulator with an integrated high-side power MOSFET. It provides up to 2 A output current. The A8587 can achieve fast transient response using current-mode control and simple external compensation.

The wide input range of 3.8 to 36 V makes the A8587 suitable for a wide range of step-down applications, including those in an automotive input environment. Battery-driven applications benefit from the low 30  $\mu$ A operational quiescent current.

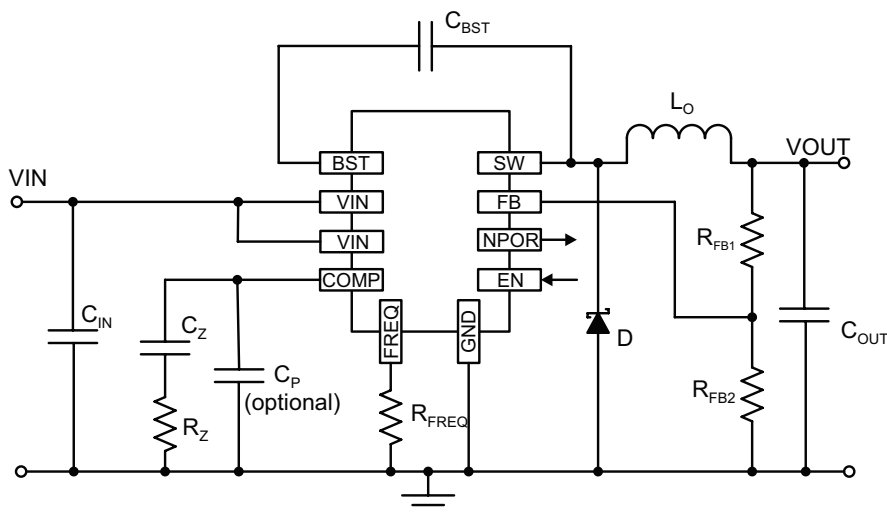
The A8587 maintains high efficiency across a wide load range by the use of pulse-frequency modulation (PFM) as the load reduces. This in turn reduces switching and gate driver losses at light load.

Frequency foldback helps to prevent inductor current runaway during startup and provides enhanced dropout performance. Extensive protection features of the A8587 include pulse-by-pulse current limit, hiccup-mode short-circuit protection, open/short freewheeling diode protection, BOOT open/short voltage protection,  $V_{IN}$  undervoltage lockout, and thermal shutdown.

The A8587 also provides an active-low power-on reset (NPOR) signal. This signal goes high—after a short delay—when  $V_{OUT}$  reaches regulation, and it goes low when  $V_{OUT}$  falls out of regulation.

The A8587 is designed to aid in EMC/EMI design by including frequency dithering, soft freewheel diode turnoff, and well-controlled switch-node slew rates. A 4 MHz oscillator allows the A8587 to switch outside EMI-sensitive frequency bands such as the AM band or ADSL bands.

The A8587 is available in an industry standard DFN10 package.



A8587 Simplified Schematic

# A8587

## Wide Input Voltage, Adjustable Frequency, 2 Amp Non-Synchronous Buck Regulator with Enable and NPOR

### SPECIFICATIONS

#### SELECTION GUIDE

Part Number	Package	Packing
A8587KEJTR-T	10-Pin DFN with Thermal Pad	1,500 pieces per 7-inch reel



#### ABSOLUTE MAXIMUM RATINGS [1]

Characteristic	Symbol	Notes	Rating	Unit
Input Voltage	$V_{IN}$		-0.3 to 40	V
Switch-Node Voltage	$V_{SW}$		-0.3 to $V_{IN}+0.3$	V
		$t < 250$ ns	-1.5	V
		$t < 50$ ns	$V_{IN}+3$	V
Bootstrap Pin to Switch Node	$V_{BST-SW}$		-0.3 to 6	V
EN, FREQ			-0.3 to $V_{IN}+0.3$	V
All Other Pins			-0.3 to 6	V
Junction Temperature	$T_J$		-40 to 150	°C
Storage Temperature Range	$T_{stg}$		-40 to 150	°C

<sup>1</sup> Stresses beyond those listed in this table may cause permanent damage to the device. The absolute maximum ratings are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the Electrical Characteristics table is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability

#### RECOMMENDED OPERATING CONDITIONS

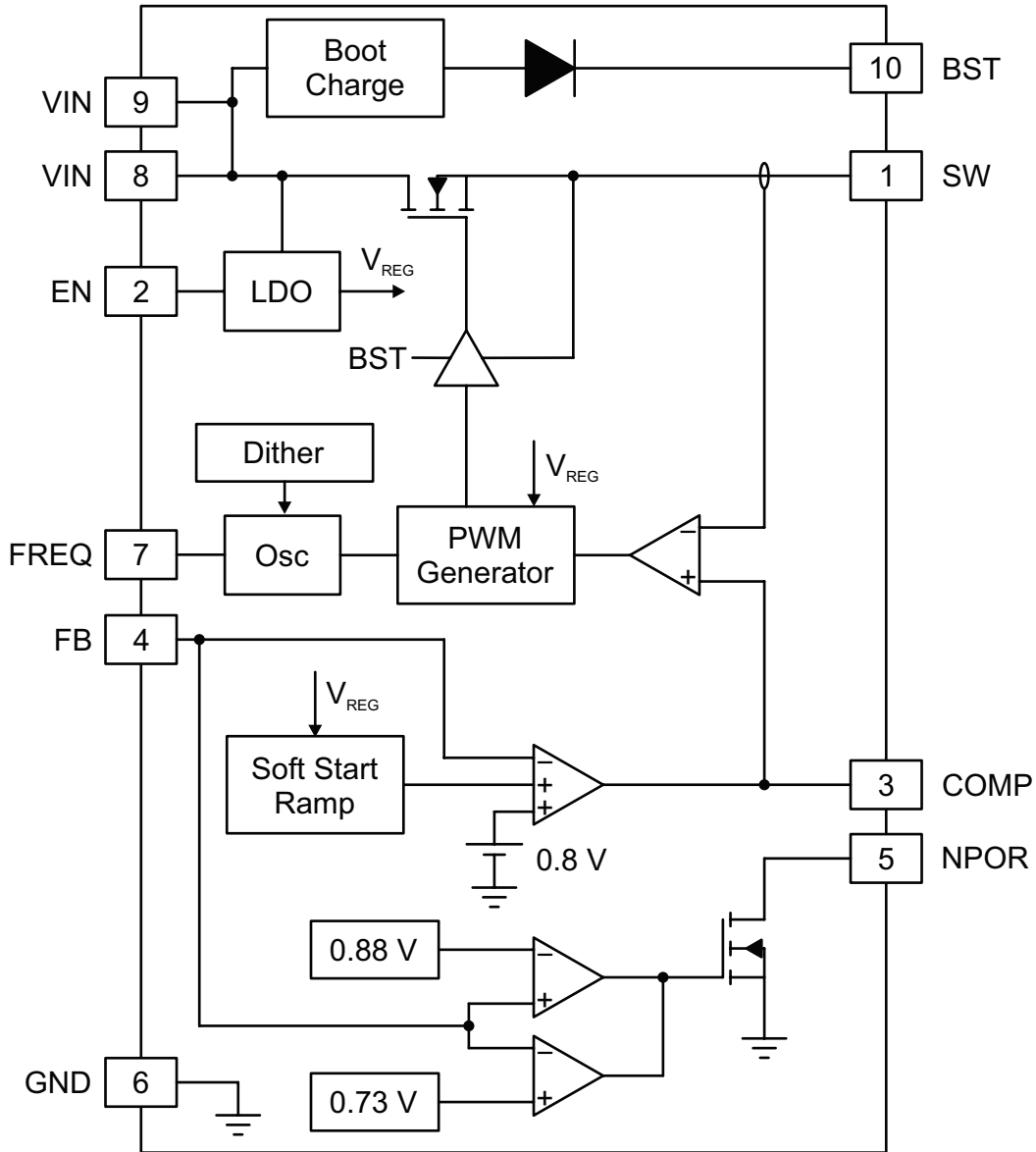
Characteristic	Symbol	Test Conditions	Value	Unit
Input Voltage	$V_{IN}$		3.8 to 36	V
Junction Temperature	$T_J$		-40 to 150	°C

#### THERMAL CHARACTERISTICS: May require derating at maximum conditions; see application information

Characteristic	Symbol	Test Conditions [2]	Value	Unit
Junction to Ambient Thermal Resistance	$R_{\theta JA}$	DFN-10 (EJ) package on 4-layer PCB based on JEDEC standard	45	°C/W

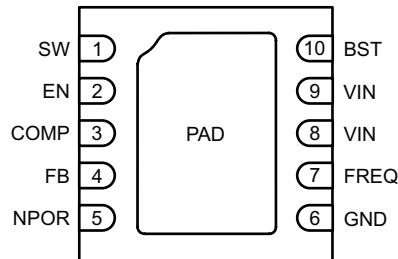
<sup>2</sup> Additional thermal information available on the Allegro website.





**Functional Block Diagram**

### PINOUT DIAGRAM AND TERMINAL LIST TABLE



Package EJ Pinouts

#### Terminal List Table

Pin Name	Pin Number	Description
SW	1	The source of the internal MOSFET. The output inductor ( $L_O$ ) and cathode of the freewheel diode (D) should be connected to this pin. $L_O$ and D should be placed as close as possible to this pin and connected with relatively wide traces.
EN	2	Enable input. This pin is a high-voltage input that turns the regulator on or off. Set this pin high to turn the regulator on or set this pin low to turn the regulator off.
COMP	3	Output of the error amplifier and compensation node for the current-mode control loop. Connect a series RC network from this pin to GND for loop compensation. See the Applications section of this datasheet for further details
FB	4	Feedback (negative) input to the error amplifier. Connect a resistor divider from the regulator output node, VOUT, to this pin to program the output voltage.
NPOR	5	Active-low power-on reset output signal. This pin is an open-drain output that transitions from low-impedance to high-impedance when the output is within the final regulation voltage.
GND	6	Ground connection.
FREQ	7	Frequency setting pin. A resistor, $R_{FREQ}$ , from this pin to GND sets the PWM switching frequency. See Table 1 and Figure 2 to determine the value of $R_{FREQ}$ .
VIN	8,9	Power input for the control circuits and the drain of the internal high-side N-channel MOSFET. Connect this pin to a power supply of 3.8 to 36 V. A high-quality ceramic capacitor should be placed very close to this pin and GND.
BST	10	Bootstrap capacitor connection. Connect a 100 nF capacitor from this pin to the SW pin. The voltage on this capacitor drives the internal MOSFET via the high-side gate driver. A series BOOT resistor is not recommended.

**ELECTRICAL CHARACTERISTICS [1]:** Valid for  $V_{IN} = 12\text{ V}$ ,  $V_{EN} = 2.5\text{ V}$ ,  $V_{COMP} = 1.4\text{ V}$ ,  $-40^{\circ}\text{C} \leq T_J \leq 125^{\circ}\text{C}$ , typical values at  $T_J = 25^{\circ}\text{C}$ , unless otherwise specified

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
<b>GENERAL SPECIFICATIONS</b>						
Operating Input Voltage	$V_{IN}$	$V_{EN} \geq 2.5\text{ V}$	3.8	12	36	V
$V_{IN}$ UVLO Start	$V_{IN(START)}$	$V_{IN}$ rising	2.6	3	3.4	V
$V_{IN}$ UVLO Hysteresis	$V_{IN(HYS)}$		–	0.4	–	V
Supply Quiescent Current [1]	$I_Q$	No load, $V_{FB} = 0.9\text{ V}$	–	27	36	$\mu\text{A}$
	$I_{Q(SLEEP)}$	$V_{EN} = 0\text{ V}$	–	11	18	$\mu\text{A}$
<b>PWM SWITCHING FREQUENCY</b>						
Switching Frequency	$f_{SW}$	$R_{FSET} = 45\text{ k}\Omega$	1.6	2.0	2.4	MHz
<b>THERMAL PROTECTION</b>						
Thermal Shutdown Threshold [2]	$T_{TSD}$	$T_J$ rising	–	170	–	$^{\circ}\text{C}$
Thermal Shutdown Hysteresis [2]	$T_{HYS}$		–	20	–	$^{\circ}\text{C}$
<b>PULSE-WIDTH MODULATION (PWM)</b>						
Minimum On-Time [2]	$t_{ON(MIN)}$		–	80	160	ns
Minimum Off-Time [2]	$t_{OFF(MIN)}$		–	100	–	ns
<b>INTERNAL MOSFET</b>						
MOSFET On-Resistance	$R_{DS(on)}$	$V_{BOOT-SW} = 5\text{ V}$	–	150	–	m $\Omega$
MOSFET Leakage	$I_{FET(LKG)}$	$V_{EN} = 0\text{ V}$ , $V_{IN} = 12\text{ V}$ , $V_{SW} = 0\text{ V}$ , $T_J = 25^{\circ}\text{C}$	–	0.1	1	$\mu\text{A}$
<b>ERROR AMPLIFIER</b>						
Feedback Voltage	$V_{FB}$	$4.5\text{ V} \leq V_{IN} \leq 36\text{ V}$ , $T_J = 25^{\circ}\text{C}$	0.786	0.792	0.803	V
		$4.5\text{ V} \leq V_{IN} \leq 36\text{ V}$ , $-40^{\circ}\text{C} \leq T_J \leq 125^{\circ}\text{C}$	0.773		0.812	V
Error Amp Voltage Gain [2]	$A_{VOL}$		–	1000	–	V/V
Error Amp Transconductance [2]	$g_m$	$I_{COMP} = \pm 3\text{ }\mu\text{A}$	35	60	95	$\mu\text{A/V}$
Error Amp Min Source Current	$I_{EA(SOURCE)}$	$V_{FB} = 0.7\text{ V}$	–	–5	–	$\mu\text{A}$
Error Amp Min Sink Current	$I_{EA(SINK)}$	$V_{FB} = 0.9\text{ V}$	–	5	–	$\mu\text{A}$
Low $I_Q$ Peak Current Threshold	$I_{PEAK(LO\_IQ)}$		–	350	–	mA
<b>SOFT-START</b>						
Soft-Start Ramp Time [2]	$t_{SS}$	$0\text{ V} < V_{FB} < 0.8\text{ V}$	–	1.5	–	ms
<b>CURRENT PROTECTION</b>						
Current Limit	$I_{LIM}$		2.3	2.7	–	A
COMP to Current-Sense Transductance [2]	$G_{CS}$		–	4.5	–	A/V
Slope Compensation	$S_{E(2MHz)}$	Measured at $f_{SW} = 2\text{ MHz}$	–	1.5	–	A/ $\mu\text{s}$
<b>LOGIC ENABLE</b>						
EN Threshold Rising	$V_{EN(H)}$	$V_{EN}$ rising	1.2	1.5	1.85	V
EN Threshold Falling	$V_{EN(L)}$	$V_{EN}$ falling	1.0	1.2	1.4	V
EN Hysteresis	$V_{EN(HYS)}$		–	300	–	mV

<sup>1</sup> For input and output current specifications, negative current is defined as coming out of the node or pin (sourcing), positive current is defined as going into the node or pin (sinking).

<sup>2</sup> Ensured by design and characterization, not production tested.

**ELECTRICAL CHARACTERISTICS [1] (continued):** Valid for  $V_{IN} = 12\text{ V}$ ,  $V_{EN} = 2.5\text{ V}$ ,  $V_{COMP} = 1.4\text{ V}$ ,  $-40^{\circ}\text{C} \leq T_J \leq 125^{\circ}\text{C}$ , typical values at  $T_J = 25^{\circ}\text{C}$ , unless otherwise specified

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
<b>POWER-ON RESET (NPOR)</b>						
Undervoltage Threshold (Falling)	$V_{NPOR(UV)}$	NPOR = low	710	730	750	mV
Undervoltage Hysteresis	$V_{NPOR(HYS)}$	NPOR = low	–	15	–	mV
Overvoltage Threshold (Rising)	$V_{NPOR(OV)}$	NPOR = low	840	880	920	mV
NPOR Rising Delay	$t_{d(NPOR)}$		5	7.5	10	ms
NPOR Output Voltage	$V_{NPOR}$	$I_{NPOR} = 10\text{ mA}$ , fault asserted	–	–	500	mV
Minimum $V_{IN}$ for Correct Operation of NPOR	$V_{IN(NPOR)}$	NPOR pull-up of $2\text{ k}\Omega$ to $5\text{ V}$	–	3.5	–	V
NPOR Leakage [2]	$I_{NPOR}$	$V_{NPOR} = 5.5\text{ V}$ , fault not asserted	–	–	1	$\mu\text{A}$

<sup>1</sup> For input and output current specifications, negative current is defined as coming out of the node or pin (sourcing), positive current is defined as going into the node or pin (sinking).

<sup>2</sup> Ensured by design and characterization, not production tested.

## FUNCTIONAL DESCRIPTION

### Overview

The A8587 is a PWM buck regulator that incorporates all of the control and protection circuitry necessary to satisfy a wide range of low-voltage applications. The A8587 employs current-mode control to provide fast transient response, simple compensation, and excellent stability.

The features of the A8587 include a  $\pm 3\%$  reference, an adjustable switching frequency, a transconductance error amplifier, an enable input, integrated power MOSFET, fixed soft-start time, and low-current sleep mode.

The protection features of the A8587 include undervoltage lockout (UVLO), cycle-by-cycle overcurrent protection (OCP), hiccup-mode short-circuit protection (HIC), overvoltage protection (OVP), and thermal shutdown (TSD).

### PWM Control

The A8587 includes a high-speed PWM comparator, capable of pulse widths less than 100 ns. The inverting input of the comparator is connected to the output of the error amplifier. The non-inverting input is connected to the current-sense signal.

At the beginning of each PWM cycle, the PWM\_CLK signal sets the PWM flip-flop and the high-side MOSFET is turned on. When the current-sense signal rises above the error amplifier voltage, the comparator resets the PWM flip-flop and the high-side MOSFET is turned off. It remains off for at least 100 ns before the next cycle can be initiated.

### Low- $I_Q$ Pulse-Frequency-Modulation (PFM) Mode

At light loads, the PFM comparator, which is connected to the FB pin, modulates the frequency of the SW node to regulate the output voltage with very high efficiency.

The reference for the PFM comparator is calibrated approximately 1% above the PWM regulation point. When the voltage at the internal FB point rises above the PFM comparator threshold and peak inductor current falls below  $I_{PEAK(LO\_IQ)}$  (800 mA) minus slope compensation, the device will enter PFM-coast mode, tri-stating the SW node and drawing extremely low current from VIN. When voltage at the FB point falls below the PFM comparator threshold, the device will fully power-up after approximately a 2.5  $\mu$ s delay, and the high-side MOSFET is repeatedly turned on, operating at the PWM switching frequency, until the voltage at the FB pin rises above the PFM comparator

threshold.  $V_{OUT}$  will rise at a rate determined by—and have a voltage ripple dependent on—the input voltage, output voltage, inductor value, output capacitance, and load. In addition, the transition point from PWM to PFM mode is defined by the input voltage, output voltage, slope compensation, and inductor value.

### Error Amplifier

The primary function of the transconductance error amplifier is to regulate the A8587 output voltage. The error amplifier appears as a device with three inputs: two positive and one negative. The negative input is simply connected to the FB pin and is used to sense the feedback voltage for regulation. The two positive inputs are connected to the internal soft-start and reference voltages. The error amplifier performs an analog OR selection between them; it regulates to either the soft-start voltage or the A8587 internal reference ( $V_{REF}$ ), whichever is lower.

To stabilize the regulator, a series RC compensation network ( $R_Z C_Z$ ) must be connected from the error amplifier output (COMP pin) to GND, as shown in the typical application schematic. In most applications, an additional low-value capacitor ( $C_p$ ) should be connected in parallel with the  $R_Z C_Z$  compensation network to roll-off the loop gain at higher frequencies. However, if the  $C_p$  capacitor is too large, the phase margin of the regulator may be reduced.

During operation, the minimum COMP voltage is clamped to 750 mV, and its maximum is clamped to 1.5 V. COMP is internally pulled down to GND during fault conditions.

### Slope Compensation

The A8587 incorporates internal slope compensation ( $S_E$ ) to allow PWM duty cycles above 50% for a wide range of input and output voltages and inductor values. The slope compensation signal is added to the sum of the current-sense amplifier output and the PWM ramp offset. The amount of slope compensation scales with the maximum on-time ( $1/f_{SW} - t_{OFF(MIN)}$ ), centered around 3.1 A/ $\mu$ s at 2 MHz. The value of the output inductor should be chosen such that  $S_E$  is between  $0.5\times$  and  $1\times$  the falling slope of the inductor current ( $S_F$ ).

### Internal Regulator

An internal series pass regulator (LDO) generates around 2.9 V for most of the internal circuits of the A8587. The power for this LDO is derived from VIN. The LDO is in full regulation once  $V_{IN}$  is greater than 3 V.



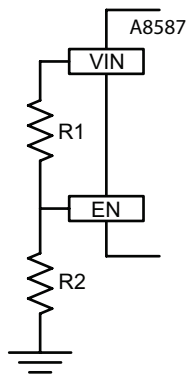
## Enable Control

The Enable (EN) input provides enabling/disabling of the A8587 with system control, or enabling/disabling of the A8587 automatically. The EN pin is rated to 40 V, so this pin may be connected directly to VIN if there is no suitable logic signal available to wake up the regulator.

When EN is used as a system-controlled enabling/disabling logic input, and EN is kept high, the A8587 turns on, and provided there are no fault conditions,  $V_{OUT}$  will ramp to its final voltage in the soft-start time. When the EN is low, the A8587 will enter shutdown mode and draw less than 20  $\mu$ A from the input.

When EN transitions low, the device waits approximately 150  $\mu$ s before shutting down. This delay provides plenty of filtering to prevent the device from prematurely entering Sleep mode because of any small glitches that might couple onto the PCB trace or EN pin.

The Enable input can also be used as a programmable UVLO. Connecting a resistor from VIN to Enable and a second resistor from Enable to ground implements this feature.



$$V_{IN(START)} = \frac{R1 + R2}{R2} \times V_{EN(H)} \quad (1)$$

$$V_{IN(STOP)} = \frac{R1 + R2}{R2} \times V_{EN(L)} \quad (2)$$

While there is an internal 1  $\mu$ A current source that pulls EN up if Enable is not used, it is recommended to connect it to VIN so the A8587 is automatically enabled once  $V_{IN}$  exceeds  $V_{IN(START)}$ .

## Undervoltage Lockout (UVLO)

An undervoltage lockout (UVLO) comparator monitors the voltage at the VIN pin and keeps the regulator disabled if the voltage is below the lockout threshold ( $V_{IN(START)}$ ). The UVLO comparator incorporates enough hysteresis ( $V_{IN(HYS)}$ ) to prevent on/off cycling of the regulator due to IR drops in the VIN path during heavy loading or during startup.

## Active-Low Power-On Reset (NPOR) Output

The Active-Low Power-On Reset (NPOR) output is an open-drain output, so an external pull-up resistor must be connected to it. An internal comparator monitors the voltage at the FB pin and controls the internal open-drain N-MOSFET at the NPOR pin. NPOR is high when the voltage at the FB pin is within regulation. At startup, there is an NPOR delay ( $t_{d(NPOR)}$ ) before NPOR goes high.

The NPOR output is pulled low if any of the following are true:

- $V_{FB}$  is rising, and is  $< V_{NPOR(UV)}$ , or
- $V_{FB}$  is rising, and is  $> V_{NPOR(OV)}$ , or
- VIN pin UVLO occurs, or
- Thermal Shutdown (TSD) occurs.

NPOR will remain low only as long as the internal circuitry is able to enhance the open-drain output device. When  $V_{IN}$  fully collapses, NPOR will return to the high-impedance state. The NPOR comparator incorporates hysteresis to prevent chattering due to voltage ripple at the FB pin.

## Low-Dropout Operation

The A8587 is designed to operate with one quarter of the switching frequency when an off-time of greater than  $t_{OFF(MIN)}$  is demanded.

## Internal Soft-Start

Inrush current to the regulator is controlled by the soft-start function. When the A8587 is enabled, after all faults are cleared, the soft-start will ramp upward from 0 to 0.8 V. The error amplifier output slews upward, and shortly thereafter, PWM switching will begin.

After the A8587 starts switching, the error amplifier will regulate the voltage at the FB pin to the internal soft-start voltage. After switching starts, the regulator output voltage will rise from 0 V to the set point determined by the feedback resistor divider ( $R_{FB1}$  and  $R_{FB2}$ ). When the voltage of the internal soft-start reaches 0.8 V, the error amplifier will change mode and begin regulating to the A8587 internal reference, 792 mV.

To keep the inductor current under control, the A8587 operates with one quarter of the switching frequency while FB remains below 200 mV, and half of the switching frequency when FB is between 200 and 400 mV. The A8587 operates at the full switching frequency when FB is greater than 400 mV.



## Pre-Biased Startup

If the output of the regulator is pre-biased to some voltage, the A8587 modifies the normal startup routine in order to prevent discharging the output capacitors. As described previously, the error amplifier usually becomes active when the soft-start voltage starts to ramp. If the output is pre-biased, the internal FB voltage is at some non-zero voltage. The COMP pin remains low and SW is tri-stated until the soft-start voltage rises above the  $V_{FB}$ .

## Thermal Shutdown

The A8587 protects itself from overheating by means of an internal thermal monitoring circuit. If the junction temperature exceeds the thermal shutdown threshold ( $T_{TSD}$ , 170°C typical), the voltages at the soft-start and COMP pins will be pulled to GND and the high-side MOSFET will be turned off. The A8587 will automatically restart when the junction temperature decreases more than the thermal shutdown hysteresis ( $T_{HYS}$ , 20°C typical).

## MOSFET Driver and Bootstrap Capacitor

The position of the internal N-channel MOSFET requires special consideration when driving it. The source of this MOSFET can be either close to  $V_{IN}$  or close to GND. For that reason, a floating gate charge driver is required. This driver requires a voltage greater than  $V_{IN}$  to ensure the MOSFET can be turned on.

A simple charge pump—consisting of an internal charge circuit, an external capacitor (BST capacitor), and the freewheeling diode—is required to power the high-side gate driver. The internal charge circuit is powered by  $V_{IN}$ . When the SW node is sufficiently below  $V_{IN}$ , the charge circuit will charge the BST capacitor to around 5 V with respect to the SW node. This BST voltage is used to turn the MOSFET on. As SW node rises, the BST capacitor will maintain the BST pin at 5 V above SW, thereby ensuring sufficient voltage to keep the MOSFET on.

Also, the BST charge circuit incorporates its own UVLO of 1.8 V rising and 0.4 V hysteresis.

## Current Comparator and Current Limit

A high-bandwidth current-sense amplifier monitors the current in the high-side MOSFET. The current signal is supplied to the PWM comparator and the cycle-by-cycle current limiter.

The cycle-by-cycle maximum current of the internal power MOSFET is internally limited.

## Overcurrent Protection (OCP) and Hiccup Mode

An OCP counter and hiccup-mode circuit protect the buck regulator when the output of the regulator is shorted to ground or when the load is too high. When the soft-start ramp is active ( $t < t_{SS}$ ), the OCP hiccup counter is disabled. Two conditions must be met for the OCP counter to be enabled and begin counting:

- $t > t_{SS}$ , and
- $V_{COMP}$  clamped at its maximum voltage ( $OCL = 1$ )

As long as these two conditions are met, the OCP counter remains enabled and counts pulses from the overcurrent comparator. If the COMP voltage decreases ( $OCL = 0$ ), the OCP counter is cleared. If the OCP counter reaches the OCPLIM counts (120), a hiccup latch is set and the COMP pin is quickly pulled down by a relatively low resistance (4 k $\Omega$ ). Switching is halted for 6 ms to provide time for the IC to cool down. After the hiccup off-time expires (6 ms), the soft-start ramp starts, marking the beginning of a new, normal soft-start cycle as described earlier. When the soft-start voltage crosses the effective output voltage, the error amplifier forces the voltage at the COMP pin to quickly slew upward and PWM switching resumes. If the short-circuit at the regulator output remains, another hiccup cycle occurs. Hiccups repeat until the short-circuit is removed or the converter is disabled. If the short-circuit has been removed, the device soft-starts normally and the output voltage automatically recovers to the target level.

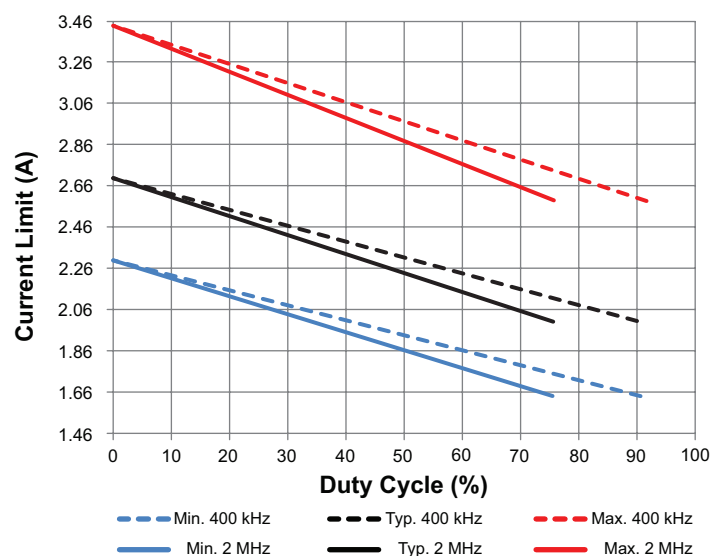


Figure 1: Current Limit versus Duty Cycle

### **BOOT Capacitor Protection**

The A8587 monitors the voltage across the BOOT capacitor to detect if the capacitor is missing or short-circuited. If the BOOT capacitor is missing, the regulator enters hiccup mode after 7 PWM cycles. If the BOOT capacitor is shorted, the regulator enters hiccup mode after 120 PWM cycles. For a BOOT fault, hiccup mode operates virtually the same as described previously for an output short-circuit fault (OCP), having a hiccup off-time of 6 ms, followed by a soft-start retry, with repeated attempts until the fault clears. However, OCP is the only fault that is ignored during the soft-start ramp time ( $t_{SS}$ ). BOOT faults are a non-latched condition, so the device automatically recovers when the fault is corrected.

### **Freewheeling Diode Protection**

If the freewheeling diode is missing or damaged (open), the SW pin is subject to unusually high negative voltages. This negative voltage may cause the device to malfunction and could lead to damage. The A8587 includes protection circuitry to detect when the freewheeling diode is missing. If the SW pin is below  $-1.25$  V typically, for more than 50 ns typically, the device enters hiccup mode after detecting one missing diode fault. Also, if the freewheeling diode is shorted, the device experiences extremely high currents through the high-side MOSFET. If this occurs, the device enters hiccup mode after detecting one shorted diode fault.

### **Overvoltage Protection (OVP)**

The A8587 provides an always-on overvoltage protection that monitors  $V_{OUT}$  to protect against  $V_{OUT}$  rising up at light loads due to high-side switch leakage. In this case, the high-side switch is forced off, and the low-side switch continues to operate and can correct the OVP condition, provided only a few milliamperes of pull-down current are required. When the condition causing the overvoltage is corrected, the regulator automatically recovers.

### **Pin-to-Ground and Pin-to-Pin Short Protections**

The A8587 is designed to satisfy the most demanding automotive applications. For example, the device is carefully designed fundamentally to withstand a short-circuit to ground at each pin without suffering damage. In addition, care was taken when defining the device pin-out to optimize protection against

adjacent pin-to-pin short-circuits. For example, logic pins and high-voltage pins are separated as much as possible. Inevitably, some low-voltage pins had to be located adjacent to high-voltage pins, but in these instances, the low-voltage pins are designed to withstand increased voltages, with clamps, series input resistance, or both, to prevent damage to the device.

### **Startup and Shutdown**

If both  $V_{IN}$  and  $V_{EN}$  are higher than their appropriate thresholds, the chip starts. The reference block starts first, generating stable reference voltage and currents, and then the internal regulator is enabled. The regulator provides stable supply for the remaining circuits.

When the internal soft-start block is enabled, it first holds its SS output low to ensure the remaining circuits are ready and then slowly ramps up.

Three events can shut down the chip:  $V_{EN}$  low,  $V_{IN}$  low, and thermal shutdown. In the shutdown procedure, the power MOSFET is turned off first to avoid any fault triggering. The COMP voltage and the internal supply rail are then pulled down.

### **Programmable Oscillator**

A resistor ( $R_{FREQ}$ ) from FREQ to ground sets the operation frequency of the A8587. The Applications Information section details the selection of this resistor.

### **Frequency Dithering**

The A8587 includes a dithering function, which changes the switching frequency within a certain frequency range. By shifting the switching frequency of the regulator in a triangle fashion around the programmed switching frequency, the overall system-noise magnitude can be greatly reduced.

The dithering sweep is internally set at  $\pm 8\%$ . The switching frequency will ramp from a low of 0.92 times the programmed frequency to a high of 1.08 times the programmed frequency. The rate or modulation at which the frequency sweeps is governed by an internal 12 kHz triangle pattern.

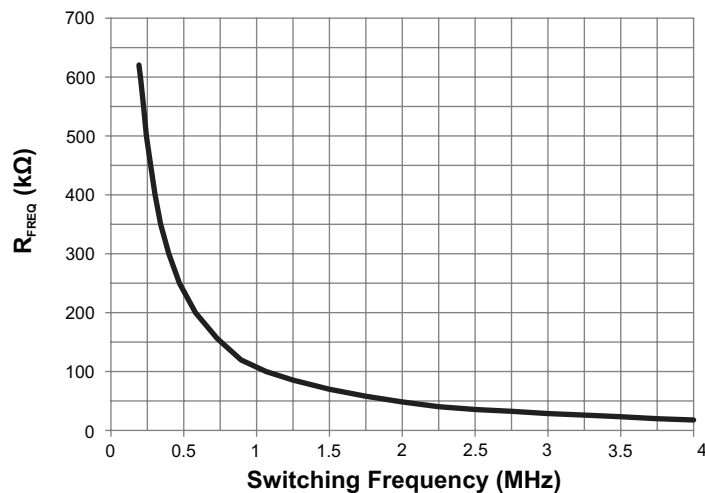
## APPLICATIONS INFORMATION

### Setting the Switching Frequency

The switching frequency ( $f_{SW}$ ) of a regulator using the A8587 can be set using a resistor at the FREQ pin ( $R_{FREQ}$ ). The recommended  $R_{FREQ}$  value for various switching frequencies can be obtained from either Table 1 or Figure 2 below:

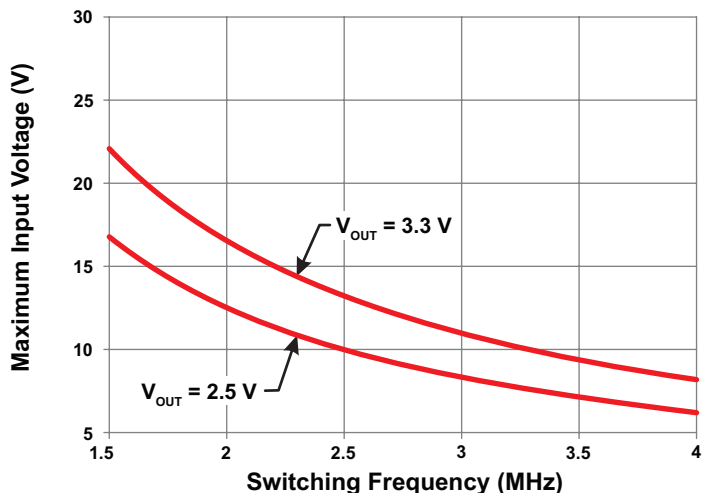
**Table 1:  $R_{FREQ}$  versus  $f_{SW}$**

$f_{SW}$ (MHz)	$R_{FREQ}$ (k $\Omega$ )
4	15.4
3.5	20
3	26.1
2.5	34
2	45.3
1.5	68.1
1	105
0.8	140
0.5	232
0.3	402
0.2	619



**Figure 2:  $R_{FREQ}$  versus  $f_{SW}$**

While the A8587 can switch at frequencies up to 4 MHz, care must be taken when operating above 2 MHz. The minimum controllable on-time for the A8587 is around 80 ns. This means at higher frequencies, pulse skipping may be seen when trying to achieve small duty cycles.



**Figure 3: Recommended Switching Frequency vs. Maximum Input Voltage**

### Setting the Output Voltage

Many output voltages can be programmed by the selection of the right resistor pair,  $R_{FB1}$  and  $R_{FB2}$ . These resistors form a voltage divider between  $V_{OUT}$  and GND with FB pin as the center. The voltage divider divides the output voltage down to the feedback voltage.

$$R_{FB1} = \frac{V_{OUT} - V_{FB}}{V_{FB}} \times R_{FB2} \quad (3)$$

Table 2 below shows some typical resistor values selected from the E48 series for popular output voltages, using  $R_{FB2} = 40.2 \text{ k}\Omega$ . More accurate output voltage set points can be achieved by using a parallel combination for  $R_{FB1}$ .

**Table 2:  $R_{FB1}$  versus  $V_{OUT}$ ,  $R_{FB2} = 40.2 \text{ k}\Omega$**

$V_{OUT}$ (V)	$R_{FB1}$ (k $\Omega$ )
1	10
1.2	20.5
1.5	34.8
1.8	51.1
2	59
2.5	86.6
2.7	95.3
3.3	127
5	215
12	562

## Inductor

As with any buck converter, an inductor is required to supply constant current to the output load while being driven by the switched input voltage. Many factors determine the selection of this inductor, such as switching frequency, output/input voltage ratio, transient response, and ripple current. A larger-value inductor will result in less ripple current that will result in lower output ripple voltage. However, the larger-value inductor will have a larger physical size, higher series resistance, and/or lower saturation current.

A good rule for determining the inductance to use is to allow the peak-to-peak ripple current in the inductor to be approximately 30% of the maximum output current ( $I_{OUT(MAX)}$ ). Also, ensure the peak inductor current during normal operation is below the maximum switch current limit. The inductance value can be calculated by:

$$L_O = \frac{V_{OUT}}{f_{SW} \times \Delta I_L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad (4)$$

where  $V_{OUT}$  is the output voltage,  $V_{IN}$  is the input voltage,  $f_{SW}$  is the switching frequency, and  $\Delta I_L$  is the peak-to-peak inductor ripple current ( $0.3 \times I_{OUT(MAX)}$ ).

A second constraint on inductor value would be loop stability at duty cycles greater than 50%. The A8587 uses current-mode control and includes internal slope compensation ( $S_E$ ). Based on the  $S_E$  value, recommended inductance for stability would be:

$$L_O \geq \frac{V_{OUT}}{S_E} \times \left(1 - 0.18 \times \frac{V_{IN(MIN)}}{V_{OUT}}\right) \quad (5)$$

Slope compensation ( $S_E$ ) will vary with switching frequency.  $S_E$  can be calculated using equation 6:

$$S_E = S_{E(2MHz)} \times \left( \frac{\frac{1}{2 \text{ MHz}} - 100 \text{ ns}}{\frac{1}{f_{SW}} - 100 \text{ ns}} \right) \quad (6)$$

Choose an inductor that will not saturate under the maximum inductor peak current, which is the current limit of the A8587, over the full temperature range.

Also, ensure the peak current at  $I_{OUT(MAX)}$  does not exceed the current limit. The peak inductor current can be calculated by:

$$I_{LPK} = I_{OUT(MAX)} + \frac{V_{OUT}}{2 \times f_{SW} \times L_O} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad (7)$$

## Freewheeling Diode

The freewheeling diode allows the current in the inductor to flow to the load when the high-side switch is off. To reduce losses due to diode forward voltage and recovery times, use a Schottky diode.

Choose a diode with a maximum reverse voltage rating greater than the maximum input voltage and a current rating greater than the maximum load current.

## Input Capacitor

Three factors should be considered when choosing the input capacitors. First, they must be chosen to support the maximum expected input voltage with adequate design margin. Second, their rms current rating must be higher than the expected rms input current to the regulator. Third, they must have enough capacitance and a low enough ESR to limit the input voltage  $dv/dt$  to something much less than the hysteresis of the VIN pin UVLO circuitry (350 mV (typ)) at maximum loading and minimum input voltage.

The input capacitor or capacitors must limit the voltage deviations at the VIN pin to something significantly less than the A8587 VIN pin UVLO hysteresis during maximum load and minimum input voltage. The minimum input capacitance can be calculated as follows:

$$C_{IN} > \frac{I_{OUT}}{0.85 \times f_{SW} \times \Delta V_{IN}} \times \frac{V_{OUT}}{V_{IN}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad (8)$$

where  $\Delta V_{IN}$  is chosen to be much less than the hysteresis of the VIN pin, UVLO comparator ( $\Delta V_{IN} \leq 100 \text{ mV}$  is recommended), and  $f_{SW}$  is the nominal PWM switching frequency.

For simplification, choose the input capacitor with an RMS current rating greater than half of the maximum load current.

## Output Capacitor

The output capacitors filter the output voltage to provide an acceptable level of ripple voltage and store energy to help maintain voltage regulation during a load transient. The voltage rating of the output capacitors must support the output voltage with sufficient design margin.

The output voltage ripple ( $\Delta V_{OUT}$ ) is a function of the output capacitor parameters:  $C_{OUT}$ , ESR, and ESL:



$$\Delta V_{OUT} = \Delta I_L \times ESR + \frac{V_{IN} - V_{OUT}}{L_O} \times ESL + \frac{\Delta I_L}{8 \times f_{SW} \times C_{OUT}} \quad (9)$$

where  $L_O$  is the inductor value, ESR is the equivalent series resistance of the output capacitor, and ESL is its equivalent series inductance.

The type of output capacitors will determine which terms of equation 9 are dominant. For ceramic output capacitors, the ESR and ESL are virtually zero, so the output voltage ripple will be dominated by the third term of equation 10:

$$\Delta V_{OUT} = \frac{\Delta I_L}{8 \times f_{SW} \times C_{OUT}} \quad (10)$$

To reduce the voltage ripple of a design using ceramic output capacitors, simply increase the total capacitance, reduce the inductor current ripple (that is, increase the inductor value), or increase the switching frequency.

For electrolytic output capacitors, the value of capacitance will be relatively high, so the third term in equation 9 will be very small. The output voltage ripple will be determined primarily by the first two terms of equation 9:

$$\Delta V_{OUT} = \Delta I_L \times ESR + \frac{V_{IN} - V_{OUT}}{L_O} \times ESL \quad (11)$$

To reduce the voltage ripple of a design using electrolytic output capacitors, simply decrease the equivalent ESR and ESL by using a higher-quality capacitor, add more capacitors in parallel, or reduce the inductor current ripple (that is increase the inductor value).

The ESR of some electrolytic capacitors can be quite high, so Allegro recommends choosing a quality capacitor that clearly documents the ESR, or the total impedance, in the datasheet. Also, the ESR of electrolytic capacitors usually increases significantly at cold temperatures—by as much as  $10\times$ —which increases the output voltage ripple and in most cases significantly reduces the stability of the system.

The transient response of the regulator depends on the number and type of output capacitors. In general, minimizing the ESR of the output capacitance will result in a better transient response. The ESR can be minimized by simply adding more capacitors in parallel or by using higher-quality capacitors. At the instant of a fast load transient ( $di/dt$ ), the output voltage will change by the amount:

$$\Delta V_{OUT} = \Delta I_{OUT} \times ESR + \frac{di}{dt} \times ESL \quad (12)$$

After the load transient occurs, the output voltage will deviate from its nominal value for a short time. This time will depend on the system bandwidth, the output inductor value, and output capacitance. Eventually, the error amplifier will bring the output voltage back to its nominal value.

The speed at which the error amplifier will bring the output voltage back to its set point will depend mainly on the closed-loop bandwidth of the system. A higher bandwidth usually results in a shorter time to return to the nominal voltage. However, acceptable gain and phase margins may be more difficult to obtain with a higher-bandwidth system. Selection of the compensation components ( $R_Z$ ,  $C_Z$ ,  $C_P$ ) are discussed in more detail in the Compensation Components section of this datasheet.

## Low-I<sub>Q</sub> PFM Output Voltage Ripple Calculation

After choosing an output inductor and an output capacitor or capacitors, it is important to calculate the output voltage ripple ( $\Delta V_{OUT(PFM)}$ ) during Low-I<sub>Q</sub> PFM mode. With ceramic output capacitors, the output voltage ripple in PWM mode is usually negligible, but that is not the case during Low-I<sub>Q</sub> PFM mode.

The PFM-mode comparator requires about 10 mV or greater of voltage ripple on the VOUT pin and generates groups of pulses to meet this requirement. However, if a single pulse results in a voltage ripple greater than 10 mV, then the voltage ripple would be dictated by that single pulse. To calculate the voltage ripple from that single pulse, first the peak inductor current must be calculated with slope compensation taken into account. The  $I_{PEAK(LO\_IQ)}$  specification does not include slope compensation; therefore, the peak inductor current operating point is calculated as follows:

$$I_{PEAK\_L} = \frac{I_{PEAK(LO\_IQ)}}{1 + \frac{S_E \times L_O}{V_{IN} - V_{OUT}}} \quad (13)$$

Then, calculate the MOSFET on-time ( $t_{ON(Q)}$ ) and freewheeling diode on-time ( $t_{ON(D)}$ ) (Figure 3). The on-time is defined as the time it takes for the inductor current to reach  $I_{PEAK\_L}$ :

$$t_{ON(Q)} = \frac{I_{PEAK\_L} \times L_O}{V_{IN} - V_{OUT} - I_{PEAK\_L} \times (R_{DS(on)HS} + L_{O(DCR)})} \quad (14)$$

where  $R_{DS(on)}$  is the on-resistance of the internal high-side MOSFET (150 mΩ typical) and  $L_{O(DCR)}$  is the DC resistance of the

output inductor ( $L_O$ ). During this rising time interval, the length of time for the inductor current to rise from 0 A to  $I_{OUT}$  is:

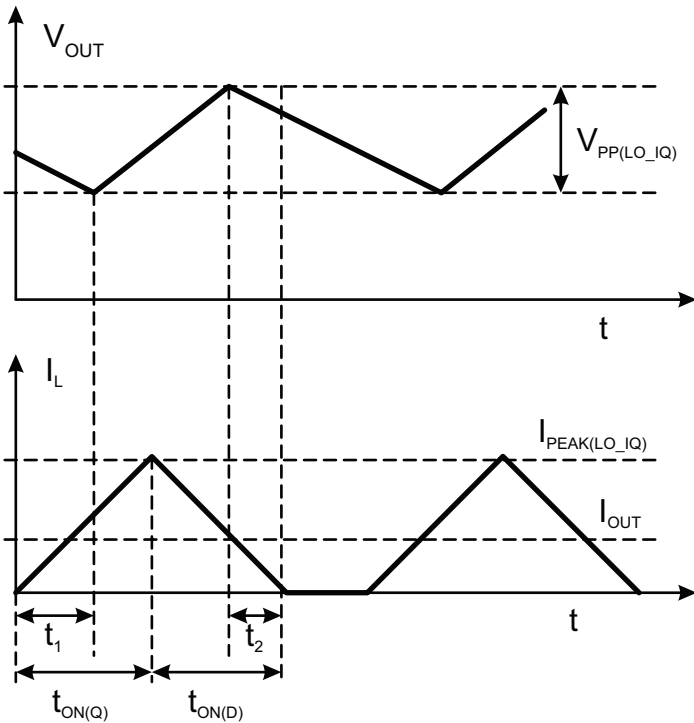
$$t_1 = \frac{I_{OUT} \times L_O}{V_{IN} - V_{OUT} - I_{PEAK\_L} \times (R_{DS(on)HS} + L_{O(DCR)})} \quad (15)$$

The freewheeling diode on-time is defined as the time it takes for the inductor current to decay from  $I_{PEAK\_L}$  to 0 A:

$$t_{ON(D)} = \frac{I_{PEAK\_L} \times L_O}{V_{OUT} + V_F} \quad (16)$$

During this falling time interval, the length of time for the inductor current to fall from  $I_{OUT}$  to 0 A is:

$$t_2 = \frac{I_{OUT} \times L_O}{V_{OUT} + V_F} \quad (17)$$



**Figure 4: Calculating the Output Ripple Voltage in PFM Mode**

Given the peak inductor current ( $I_{PEAK\_L}$ ) and the rise and fall times ( $t_{ON(Q)}$  and  $t_{ON(D)}$ ) for the inductor current, the output voltage ripple can be calculated for a signal pulse as follows:

$$V_{PP(LO\_IQ)} = \frac{I_{PEAK\_L} - I_{OUT}}{2 \times C_{OUT}} \times (t_{ON(Q)} + t_{ON(D)} - t_1 - t_2) \quad (18)$$

If  $V_{PP(LO\_IQ)}$  is greater than the  $\sim 10$  mV ripple that the PFM comparator requires, then the output capacitance or inductor can be adjusted to reduce the PFM-mode voltage ripple. In PFM mode, decreasing the inductor value reduces the PFM ripple, but may negatively impact the PWM voltage ripple, maximum load current in PWM mode, or change the mode of operation from CCM to DCM.

If  $V_{PP(LO\_IQ)}$  is less than the  $\sim 10$  mV requirement, the A8587 operates with multiple pulses at the PWM frequency to meet the ripple requirement. The fixed-frequency operation may result in DCM or CCM operation during the multiple pulses.

### Compensation Components

A8587 employs current-mode control for easy compensation and fast transient response. The system stability and transient response are controlled through the COMP pin. COMP pin is the output of the internal transconductance error amplifier. A series capacitor-resistor combination sets a pole-zero pair to control the characteristics of the control system. The DC voltage gain,  $A_{VDC}$ , of the feedback loop is given by:

$$A_{VDC} = \frac{V_{OUT}}{I_{OUT}} \times G_{CS} \times A_{VOL} \times \frac{V_{FB}}{V_{OUT}} \quad (19)$$

where  $A_{VOL}$  is the error amplifier voltage gain, 1000 V/V.  $G_{CS}$  is the current-sense transconductance, 9 A/V.

The system has two noteworthy poles: one is due to the compensation capacitor ( $C_Z$ ) and the error amplifier output resistor; the other is due to the output capacitor and the load resistor. These poles are located at:

$$f_{P1} = \frac{g_m}{2\pi \times C_Z \times A_{VOL}} \quad (20)$$

$$f_{P2} = \frac{I_{OUT}}{2\pi \times C_{OUT} \times V_{OUT}} \quad (21)$$

where  $g_m$  is the error amplifier transconductance, 60  $\mu$ A/V.

The system has one noteworthy zero. This is due to the compensation capacitor ( $C_Z$ ) and the compensation resistor ( $R_Z$ ). This zero is located at:

$$f_Z = \frac{1}{2\pi \times C_Z \times R_Z} \quad (22)$$

The system may have another zero, if the output capacitor has a large capacitance, or a high ESR value, or both. The zero, due to the ESR and capacitance of the output capacitor, is located at:

$$f_z = \frac{1}{2\pi \times C_{OUT} \times ESR} \quad (23)$$

In this case (as shown in the simplified schematic on page 1), a third pole set by the optional compensation capacitor ( $C_p$ ) and the compensation resistor ( $R_z$ ) is used to compensate the effect of the ESR zero on the loop gain. This pole is located at:

$$f_{p3} = \frac{1}{2\pi \times C_p \times R_z} \quad (24)$$

The goal of compensation design is to shape the converter transfer function to get a desired loop gain. The system crossover frequency where the feedback loop has unity gain is important. Lower crossover frequencies result in slower line and load transient responses, while higher crossover frequencies could cause the system to be unstable. A good rule of thumb is to set the crossover frequency to approximately one tenth of the switching frequency. Table 3 lists typical values of compensation components for some standard output voltages with various output ceramic capacitors and inductors. The values of the compensation components have been optimized for fast transient responses and good stability.

**Table 3: Compensation Values for Typical Output Voltage/ Capacitor Combinations with  $f_{SW} = 500$  kHz**

$V_{OUT}$ (V)	$L_O$ ( $\mu$ H)	$C_{OUT}$ ( $\mu$ F)	$R_z$ (k $\Omega$ )	$C_z$ (pF)	$C_p$
1.8	4.7	47	105	100	None
2.5	4.7 to 6.8	22	54.9	220	None
3.3	6.8 to 10	22	68.1	220	None
5	15 to 22	22	100	150	None
12	22 to 33	22	147	150	None

To optimize the compensation components for conditions not listed in Table 3, the following procedure can be used:

1. Choose the compensation resistor ( $R_z$ ) to set the desired crossover frequency ( $f_c$ ). Determine the  $R_z$  value by the following equation:

$$R_z = \frac{2\pi \times C_{OUT} \times f_c}{g_m \times G_{CS}} \times \frac{V_{OUT}}{V_{FB}} \quad (25)$$

2. Choose the compensation capacitor ( $C_z$ ) to achieve the desired phase margin. For applications with typical inductor

values, setting the compensation zero ( $f_{z1}$ ) below one fourth of the crossover frequency provides sufficient phase margin. Determine the  $C_z$  value by the following equation:

$$C_z > \frac{4}{2\pi \times R_z \times f_c} \quad (26)$$

3. Determine if the second compensation capacitor ( $C_p$ ) is required. It is required if the ESR zero of the output capacitor is located at less than half of the switching frequency or the following relationship is valid:

$$\frac{1}{2\pi \times C_{OUT} \times ESR} < \frac{f_{sw}}{2} \quad (27)$$

If this is the case, then add the second compensation capacitor ( $C_p$ ) to set the pole  $f_{p3}$  at the location of the ESR zero. Determine the  $C_p$  value by the equation:

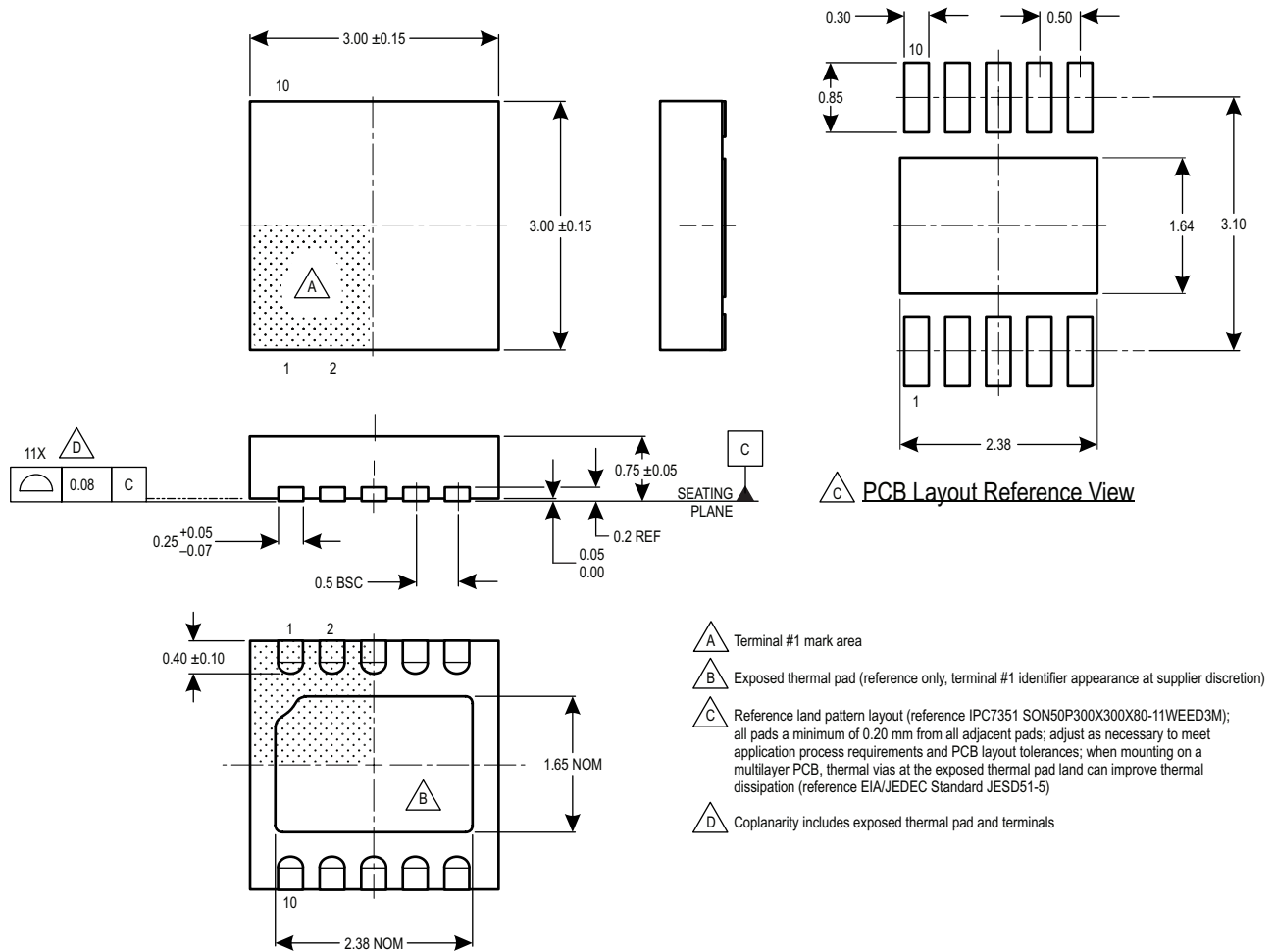
$$C_p = \frac{C_{OUT} \times ESR}{R_z} \quad (28)$$



**PACKAGE OUTLINE DRAWING**

**For Reference Only – Not for Tooling Use**

(Reference DWG 2860)  
Dimensions in millimeters – NOT TO SCALE  
Exact case and lead configuration at supplier discretion within limits shown



**Figure 5: Package EJ, 10-Pin DFN with Exposed Thermal Pad**

**Revision History**

Number	Date	Description
–	March 25, 2016	Initial release.
1	October 4, 2016	Removed “Operating at Low Input Voltages” section (page 9 and 15).
2	January 17, 2017	Corrected EJ package outline drawing (page 16). Updated bootstrap capacitor value (page 4).

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