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80V Synchronous 4-Switch Buck-Boost DC/DC Controller with Flexible Bidirectional Capability

FEATURES

- **Single Inductor Allows V_{IN} Above, Below, or Equal to V_{OUT}**
- **Six Independent Forms of Regulation**
  - **V_{IN} Current (Forward and Reverse)**
  - **V_{OUT} Current (Forward and Reverse)**
  - **V_{IN} and V_{OUT} Voltage**
- **Forward and Reverse Discontinuous Conduction Mode Supported**
- **Supports MODE and DIR Pin Changes While Switching**
- **V_{INCHIP} Range 2.8V (Need $EXTV_{CC}$ > 6.4V) to 80V**
- **V_{OUT} Range: 1.3V to 80V**
- **Synchronous Rectification: Up to 99% Efficiency**
- Available in 40-Lead (5mm × 8mm) QFN with High Voltage Pin Spacing

APPLICATIONS

- High Voltage Buck-Boost Converters
- Bidirectional Charging System
- Automotive 48V Systems

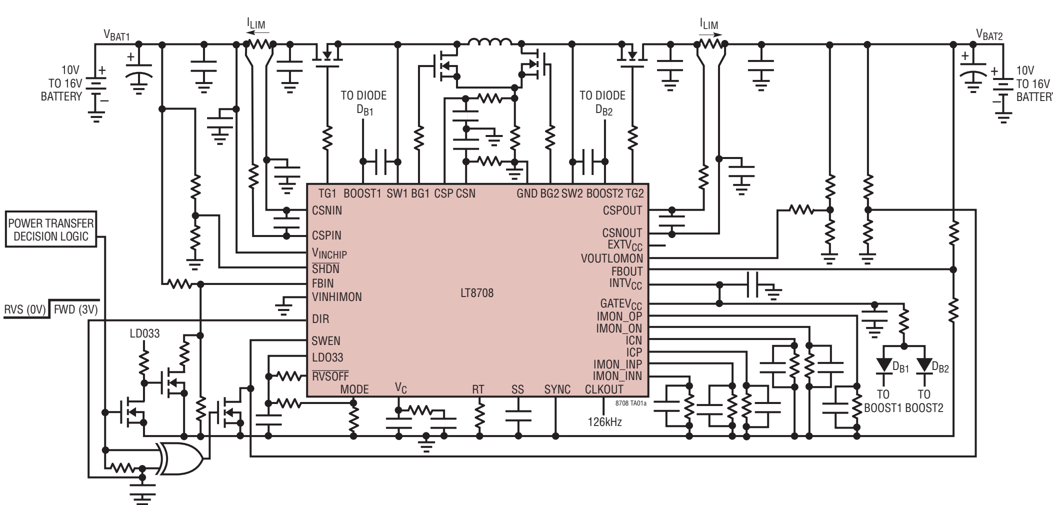
DESCRIPTION

The LT®8708 is a high performance buck-boost switching regulator controller that operates from an input voltage that can be above, below or equal to the output voltage. Features are included to simplify bidirectional power conversion in battery/capacitor backup systems and other applications that may need regulation of V_{OUT}, V_{IN}, I_{OUT}, and/or I_{IN}. Forward and reverse current can be monitored and limited for the input and output sides of the converter. All four current limits (forward input, reverse input, forward output and reverse output) can be set independently using four resistors on the PCB.

The MODE pin can select between discontinuous conduction mode (DCM), continuous conduction mode (CCM), hybrid conduction mode (HCM) and Burst Mode® operation. In combination with the DIR (direction) pin, the chip can be configured to process power only from V_{IN} to V_{OUT} or only from V_{OUT} to V_{IN}. With a wide 2.8V to 80V input and 1.3V to 80V output range, the LT8708 is compatible with most solar, automotive, telecom and battery-powered systems.

TYPICAL APPLICATION

12V Bidirectional Dual Battery System with FHCM and RHCM



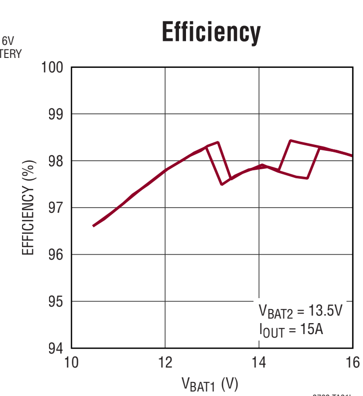


TABLE OF CONTENTS

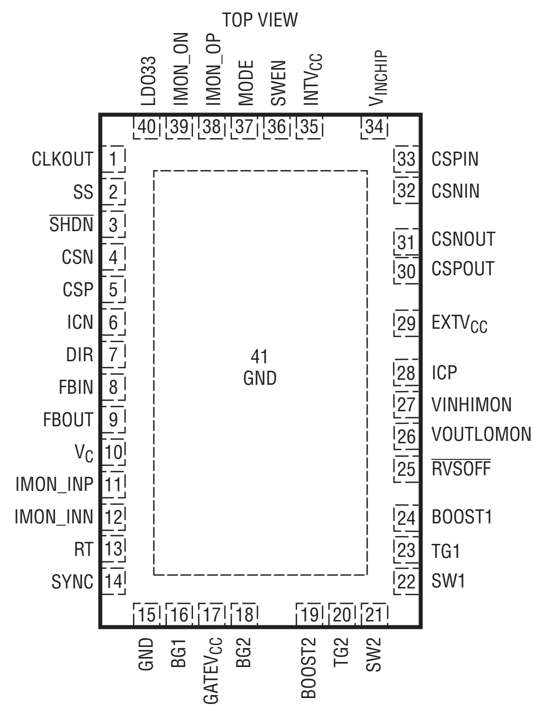
Rev 0

ABSOLUTE MAXIMUM RATINGS

(Note 1)

$V_{CSP} – V_{CSN}$, $V_{CSPIN} – V_{CSNIN}$,
$V_{CSPOUT} – V_{CSNOUT}$ .... –0.3V to 0.3V
CSP, CSN Voltage.. –0.3V to 3V
V_C Voltage (Note 2) .... –0.3V to 2.2V
RT, FBOUT, SS Voltage .... –0.3V to 5V
IMON_INP, IMON_INN, IMON_OP, IMON_ON,
ICP, ICN Voltage...................................... –0.3V to 5V
SYNC Voltage.. –0.3V to 5.5V
$INTV_{CC}$, $GATEV_{CC}$ Voltage............................ –0.3V to 7V
$V_{BOOST1} – V_{SW1}$, $V_{BOOST2} – V_{SW2}$................ –0.3V to 7V
SWEN, $\overline{RVSOFF}$ Voltage .... –0.3V to 7V
SWEN Current...0.5mA
$\overline{RVSOFF}$ Current 1mA
FBIN, $\overline{SHDN}$ Voltage .... –0.3V to 30V
VINHIMON Voltage.................................... –0.3V to 30V
VOUTLOMON Voltage .... –0.3V to 5V
DIR, MODE Voltage...................................... –0.3V to 5V
CSNIN, CSPIN, CSPOUT, CSNOUT Voltage –0.3V to 80V
V_{INCHIP}, $EXTV_{CC}$ Voltage .... –0.3V to 80V
SW1, SW2 Voltage .... 81V (Note 6)
BOOST1, BOOST2 Voltage .... –0.3V to 87V
BG1, BG2, TG1, TG2 .... (Note 5)
LDO33, CLKOUT .... (Note 8)
Operating Junction Temperature Range
LT8708E (Notes 3, 8)........................ –40°C to 125°C
LT8708I (Notes 3, 8).......................... –40°C to 125°C
LT8708H (Notes 3, 8) .... –40°C to 150°C
Storage Temperature Range ....–65°C to 150°C

PIN CONFIGURATION



UHG PACKAGE
40-LEAD (5mm × 8mm) PLASTIC QFN
T_{JMAX} = 150°C, θ_{JA} = 36°C/W, θ_{JC} = 3.8°C/W
EXPOSED PAD (PIN 41) IS GND, MUST BE SOLDERED TO PCB

ORDER INFORMATION

LEAD FREE FINISH	TAPE AND REEL	PART MARKING*	PACKAGE DESCRIPTION	TEMPERATURE RANGE
LT8708EUHG#PBF	LT8708EUHG#TRPBF	8708	40-Lead (5mm × 8mm) Plastic QFN	–40°C to 125°C
LT8708IUHG#PBF	LT8708IUHG#TRPBF	8708	40-Lead (5mm × 8mm) Plastic QFN	–40°C to 125°C
LT8708HUHG#PBF	LT8708HUHG#TRPBF	8708	40-Lead (5mm × 8mm) Plastic QFN	–40°C to 150°C

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

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

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_{INCHIP} = 12V, $\overline{SHDN}$ = 3V, DIR = 3.3V unless otherwise noted (Note 3).

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
Voltage Supplies and Regulators						
V_{INCHIP} Operating Voltage Range	$EXTV_{CC}$ = 0V $EXTV_{CC}$ = 7.5V	● ●	5.5 2.8		80 80	V V
V_{INCHIP} Quiescent Current	Not Switching, V_{EXTVCC} = 0V SWEN = 3.3V SWEN = 0V			 3.9 2.45	 6.5 4.5	 mA mA
V_{INCHIP} Quiescent Current in Shutdown	$V_{\overline{SHDN}}$ = 0V			0	1	μA
$EXTV_{CC}$ Switchover Voltage	I_{INTVCC} = –20mA, V_{EXTVCC} Rising	●	6.15	6.4	6.6	V
$EXTV_{CC}$ Switchover Hysteresis				0.2		V
$INTV_{CC}$ Current Limit	Maximum Current Draw from $INTV_{CC}$ and LDO33 Pins Combined. Regulated from V_{INCHIP} or $EXTV_{CC}$ (12V) $INTV_{CC}$ = 5.25V $INTV_{CC}$ = 4.4V	 ● ●	 90 28	 127 42	 165 55	 mA mA
$INTV_{CC}$ Voltage	Regulated from V_{INCHIP}, I_{INTVCC} = 20mA Regulated from $EXTV_{CC}$ (12V), I_{INTVCC} = 20mA	● ●	6.1 6.1	6.3 6.3	6.5 6.5	V V
$INTV_{CC}$ Load Regulation	I_{INTVCC} = 0mA to 50mA			–0.5	–1.5	%
$INTV_{CC}$, $GATEV_{CC}$ Undervoltage Lockout	$INTV_{CC}$ Falling, $GATEV_{CC}$ Connected to $INTV_{CC}$	●	4.45	4.65	4.85	V
$INTV_{CC}$, $GATEV_{CC}$ Undervoltage Lockout Hysteresis	$GATEV_{CC}$ Connected to $INTV_{CC}$			170		mV
$INTV_{CC}$ Regulator Dropout Voltage	V_{INCHIP} – V_{INTVCC}, I_{INTVCC} = 20mA			220		mV
LDO33 Pin Voltage	5mA from LDO33 Pin	●	3.23	3.295	3.35	V
LDO33 Pin Load Regulation	I_{LDO33} = 0.1mA to 5mA			–0.25	–1	%
LDO33 Pin Current Limit	SYNC = 3V	●	12	17.25	22	mA
LDO33 Pin Undervoltage Lockout	LDO33 Falling		2.96	3.04	3.12	V
LDO33 Pin Undervoltage Lockout Hysteresis				35		mV
Switching Regulator Control						
Maximum Current Sense Threshold (V_{CSP} – V_{CSN})	Boost Mode, Minimum M3 Switch Duty Cycle	●	76	93	110	mV
Maximum Current Sense Threshold (V_{CSN} – V_{CSP})	Buck Mode, Minimum M2 Switch Duty Cycle	●	68	82	97	mV
Maximum Current Sense Threshold (V_{CSN} – V_{CSP})	Boost Mode, Minimum M3 Switch Duty Cycle	●	79	93	108	mV
Maximum Current Sense Threshold (V_{CSP} – V_{CSN})	Buck Mode, Minimum M2 Switch Duty Cycle	●	72	84	96	mV
Gain from V_C to Maximum Current Sense Voltage (V_{CSP} – V_{CSN}) (A5 in the Block Diagram)	Boost Mode Buck Mode			135 –135		mV/V mV/V
$\overline{SHDN}$ Input Voltage High	$\overline{SHDN}$ Rising to Enable the Device	●	1.175	1.221	1.275	V
$\overline{SHDN}$ Input Voltage High Hysteresis				40		mV
$\overline{SHDN}$ Input Voltage Low	Device Disabled, Low Quiescent Current (LT8708E, LT8708I) (LT8708H)	 ● ●			 0.35 0.3	 V V
$\overline{SHDN}$ Pin Bias Current	$V_{\overline{SHDN}}$ = 3V $V_{\overline{SHDN}}$ = 12V			0 14	1 22	μA μA
SWEN Rising Threshold Voltage		●	1.156	1.208	1.256	V
SWEN Threshold Voltage Hysteresis				22		mV
SWEN Output Voltage Low	I_{SWEN} = 200μA $\overline{SHDN}$ = 0V or V_{INCHIP} = 0V $\overline{SHDN}$ = 3V	 ● ●		 0.9 0.2	 1.1 0.5	 V V

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_{INCHIP} = 12V, $\overline{SHDN}$ = 3V, DIR = 3.3V unless otherwise noted (Note 3).

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
SWEN Internal Pull-Down Release Voltage	$\overline{SHDN}$ = 3V	●	0.75	0.8		V
MODE Pin Continuous Conduction Mode (CCM) Threshold		●	0.4			V
MODE Pin Hybrid DCM/CCM Mode (HCM) Range		●	0.8		1.2	V
MODE Pin Discontinuous Conduction Mode (DCM) Range		●	1.6		2.0	V
MODE Pin Burst Mode Operation Threshold		●			2.4	V
DIR Pin Forward Operation Threshold		●	1.6			V
DIR Pin Reverse Operation Threshold		●			1.2	V
$\overline{RVSOFF}$ Output Voltage Low	$I_{\overline{RVSOFF}}$ = 200µA	●		0.08	0.5	V
$\overline{RVSOFF}$ Falling Threshold Voltage		●	1.155	1.209	1.275	V
$\overline{RVSOFF}$ Threshold Voltage Hysteresis				165		mV
Soft-Start Charging Current	V_{SS} = 0V		13	19	25	µA
ICN Rising Threshold for FDCM Operation	MODE = 1V (HCM), DIR = 3.3V	●	235	255	280	mV
ICN Falling Threshold for CCM Operation	MODE = 1V (HCM), DIR = 3.3V	●	185	205	235	mV
IMON_INP Rising Threshold for RDCM Operation	MODE = 1V (HCM), DIR = 0V	●	235	255	280	mV
IMON_INP Falling Threshold for CCM Operation	MODE = 1V (HCM), DIR = 0V	●	185	205	235	mV
Voltage Regulation Loops (Refer to Block Diagram to Locate Amplifiers)						
Regulation Voltage for FBOUT	Regulate V_C to 1.2V	●	1.193	1.207	1.222	V
Regulation Voltage for FBIN	Regulate V_C to 1.2V	●	1.184	1.205	1.226	V
Line Regulation for FBOUT and FBIN Error Amp Reference Voltage	V_{INCHIP} = 12V to 80V. Not Switching			0.002	0.005	%/V
FBOUT Pin Bias Current	Current Out of Pin			15		nA
FBOUT Error Amp EA4 g_m				345		µmho
FBOUT Error Amp EA4 Voltage Gain				245		V/V
VOUTLOMON Voltage Activation Threshold	Falling	●	1.185	1.207	1.225	V
VOUTLOMON Threshold Voltage Hysteresis				24		mV
VOUTLOMON Pin Bias Current	$V_{VOUTLOMON}$ =1.24V, Current Into Pin $V_{VOUTLOMON}$ =1.17V, Current Into Pin	 ●	 0.8	0.01 1	 1.2	µA µA
FBIN Pin Bias Current	Current Out of Pin			10		nA
FBIN Error Amp EA3 g_m				235		µmho
FBIN Error Amp EA3 Voltage Gain				150		V/V
VINHIMON Voltage Activation Threshold	Rising	●	1.185	1.207	1.23	V
VINHIMON Threshold Voltage Hysteresis				24		mV
VINHIMON Pin Bias Current	$V_{VINHIMON}$ = 1.17V, Current Out of Pin $V_{VINHIMON}$ = 1.24V, Current Out of Pin	 ●	 0.8	0.03 1	 1.2	µA µA
Current Regulation Loops (Refer to Block Diagram to Locate Amplifiers)						
Regulation Voltages for IMON_INP and IMON_OP	V_C = 1.2V	●	1.185	1.209	1.231	V
Regulation Voltages for IMON_INN and IMON_ON	V_C =1.2V	●	1.185	1.21	1.24	V

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_{INCHIP} = 12V, $\overline{SHDN}$ = 3V, DIR = 3.3V unless otherwise noted (Note 3).

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
Line Regulation for IMON_INP, IMON_INN, IMON_OP and IMON_ON Error Amp Reference Voltage	V_{INCHIP} = 12V to 80V			0.002	0.005	%/V
CSPIN Bias Current	V_{CSPIN} = 12V V_{CSPIN} = 1.5V			0.01 0.01		µA µA
CSNIN Bias Current	BOOST Capacitor Charge Control Block Not Active V_{SWEN} = 3.3V, V_{CSPIN} = V_{CSNIN} = 12V V_{SWEN} = 3.3V, V_{CSPIN} = V_{CSNIN} = 1.5V V_{SWEN} = 0V			 84 4.25 0.01		 µA µA µA
CSPIN, CSNIN Common Mode Operating Voltage Range		●	0		80	V
CSPIN, CSNIN Differential Mode Operating Voltage Range		●	–100		100	mV
IMON_INP Output Current	V_{CSPIN} – V_{CSNIN} = 50mV, V_{CSNIN} = 5V V_{CSPIN} – V_{CSNIN} = 50mV, V_{CSNIN} = 5V V_{CSPIN} – V_{CSNIN} = 5mV, V_{CSNIN} = 5V V_{CSPIN} – V_{CSNIN} = 5mV, V_{CSNIN} = 5V	 ● ●	67 64.5 22.5 20	70 70 25 25	73 75.5 27.5 30	µA µA µA µA
IMON_INN Output Current	V_{CSNIN} – V_{CSPIN} = 50mV, V_{CSNIN} = 5V V_{CSNIN} – V_{CSPIN} = 50mV, V_{CSNIN} = 5V V_{CSNIN} – V_{CSPIN} = 5mV, V_{CSNIN} = 5V V_{CSNIN} – V_{CSPIN} = 5mV, V_{CSNIN} = 5V	 ● ●	66 65 19 18	70 70 25 25	74 75 30.5 32	µA µA µA µA
IMON_INP and IMON_INN Max Output Current		●	120			µA
IMON_INP Error Amp EA5 g_m				190		µmho
IMON_INP Error Amp EA5 Voltage Gain				130		V/V
IMON_INN Error Amp EA1 g_m	FBIN = 0V, FBOUT = 3.3V			190		µmho
IMON_INN Error Amp EA1 Voltage Gain	FBIN = 0V, FBOUT = 3.3V			130		V/V
CSPOUT Bias Current	V_{CSPOUT} = 12V V_{CSPOUT} = 1.5V			0.01 0.01		µA µA
CSNOUT Bias Current	BOOST Capacitor Charge Control Block Not Active V_{SWEN} = 3.3V, V_{CSPOUT} = V_{CSNOUT} = 12V V_{SWEN} = 3.3V, V_{CSPOUT} = V_{CSNOUT} = 1.5V V_{SWEN} = 0V			 83 4.25 0.01		 µA µA µA
CSPOUT, CSNOUT Common Mode Operating Voltage Range		●	0		80	V
CSPOUT, CSNOUT Differential Mode Operating Voltage Range		●	–100		100	mV
IMON_OP, ICP Output Current	V_{CSPOUT} – V_{CSNOUT} = 50mV, V_{CSNOUT} = 5V V_{CSPOUT} – V_{CSNOUT} = 50mV, V_{CSNOUT} = 5V V_{CSPOUT} – V_{CSNOUT} = 5mV, V_{CSNOUT} = 5V V_{CSPOUT} – V_{CSNOUT} = 5mV, V_{CSNOUT} = 5V V_{CSPOUT} – V_{CSNOUT} = –5mV, V_{CSNOUT} = 5V V_{CSPOUT} – V_{CSNOUT} = –5mV, V_{CSNOUT} = 5V	 ● ● ●	67 65 22.5 20.5 12.5 10.5	70 70 25 25 15 15	73 76 27.5 29 17.5 19.5	µA µA µA µA µA µA
IMON_ON, ICN Output Current	V_{CSNOUT} – V_{CSPOUT} = 50mV, V_{CSNOUT} = 5V V_{CSNOUT} – V_{CSPOUT} = 50mV, V_{CSNOUT} = 5V V_{CSNOUT} – V_{CSPOUT} = 5mV, V_{CSNOUT} = 5V V_{CSNOUT} – V_{CSPOUT} = 5mV, V_{CSNOUT} = 5V V_{CSNOUT} – V_{CSPOUT} = –5mV, V_{CSNOUT} = 5V V_{CSNOUT} – V_{CSPOUT} = –5mV, V_{CSNOUT} = 5V	 ● ● ●	67 65 22.5 20.5 12.5 10.5	70 70 25 25 15 15	73 75 27.5 29 17.5 19.5	µA µA µA µA µA µA

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_{INCHIP} = 12V, $\overline{SHDN}$ = 3V, DIR = 3.3V unless otherwise noted (Note 3).

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
IMON_OP, IMON_ON, ICP and ICN Max Output Current		●	120			µA
IMON_OP Error Amp EA6 g_m				190		µmho
IMON_OP Error Amp EA6 Voltage Gain				130		V/V
IMON_ON Error Amp EA2 gm	FBIN = 0V, FBOUT = 3.3V			190		µmho
IMON_ON Error Amp EA2 Voltage Gain	FBIN = 0V, FBOUT = 3.3V			130		V/V
NMOS Gate Drivers						
TG1, TG2 Rise Time	C_{LOAD} = 3300pF (Note 4)			20		ns
TG1, TG2 Fall Time	C_{LOAD} = 3300pF (Note 4)			20		ns
BG1, BG2 Rise Time	C_{LOAD} = 3300pF (Note 4)			20		ns
BG1, BG2 Fall Time	C_{LOAD} = 3300pF (Note 4)			20		ns
TG1 Off to BG1 On Delay	C_{LOAD} = 3300pF Each Driver			90		ns
BG1 Off to TG1 On Delay	C_{LOAD} = 3300pF Each Driver			80		ns
TG2 Off to BG2 On Delay	C_{LOAD} = 3300pF Each Driver			90		ns
BG2 Off to TG2 On Delay	C_{LOAD} = 3300pF Each Driver			80		ns
Minimum On-Time for Main Switch in Boost Operation ($t_{ON(M3,MIN)}$)	Switch M3, C_{LOAD} = 3300pF			200		ns
Minimum On-Time for Synchronous Switch in Buck Operation ($t_{ON(M2,MIN)}$)	Switch M2, C_{LOAD} = 3300pF			200		ns
Minimum Off-Time for Main Switch in Steady-State Boost Operation	Switch M3, C_{LOAD} = 3300pF			230		ns
Minimum Off-Time for Synchronous Switch in Steady-State Buck Operation	Switch M2, C_{LOAD} = 3300pF			230		ns
Oscillator						
Switch Frequency Range	SYNCing or Free Running		100		400	kHz
Switching Frequency, F_{OSC}	R_T = 365k R_T = 215k R_T = 124k	● ● ●	102 170 310	120 202 350	142 235 400	kHz kHz kHz
SYNC High Level for Synchronization		●	1.3			V
SYNC Low Level for Synchronization		●			0.5	V
SYNC Clock Pulse Duty Cycle	V_{SYNC} = 0V to 2V		20		80	%
Recommended Min SYNC Ratio F_{SYNC}/F_{OSC}				3/4		
CLKOUT Output Voltage High	V_{LDO33} – V_{CLKOUT}, 1mA Out of CLKOUT Pin, I_{LDO33} = 0µA			100	250	mV
CLKOUT Output Voltage Low	1mA Into CLKOUT Pin			25	100	mV
CLKOUT Duty Cycle	T_J = –40°C T_J = 25°C T_J = 125°C			22.7 44.1 77		% % %

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_{INCHIP} = 12V, $\overline{SHDN}$ = 3V, DIR = 3V unless otherwise noted (Note 3).

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
CLKOUT Rise Time	C_{LOAD} = 200pF			20		ns
CLKOUT Fall Time	C_{LOAD} = 200pF			20		ns
CLKOUT Phase Delay	SYNC Rising to CLKOUT Rising, f_{OSC} = 100kHz	●	160	180	200	degrees

Note 1: Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime.

Note 2: Do not force voltage on the V_C pin.

Note 3: The LT8708E is guaranteed to meet performance specifications from 0°C to 125°C junction temperature. Specifications over the –40°C to 125°C operating junction temperature range are assured by design, characterization and correlation with statistical process controls. The LT8708I is guaranteed over the full –40°C to 125°C junction temperature range. The LT8708H is guaranteed over the full –40°C to 150°C operating junction temperature range.

Note 4: Rise and fall times are measured using 10% and 90% levels. Delay times are measured using 50% levels.

Note 5: Do not apply a voltage or current source to these pins. They must be connected to capacitive loads only, otherwise permanent damage may occur.

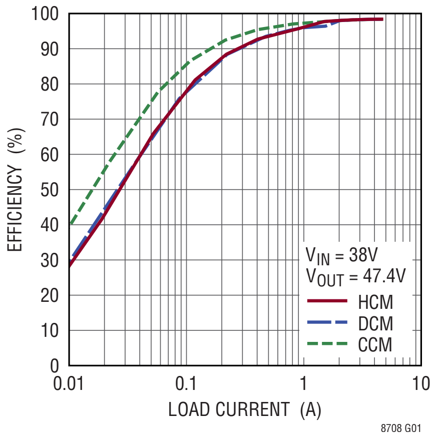
Note 6: Negative voltages on the SW1 and SW2 pins are limited, in an application, by the body diodes of the external NMOS devices, M2 and M3, or parallel Schottky diodes when present. The SW1 and SW2 pins are tolerant of these negative voltages in excess of one diode drop below ground, guaranteed by design.

Note 7: This IC includes overtemperature protection that is intended to protect the device during momentary overload conditions. Junction temperature will exceed the maximum operating junction temperature when overtemperature protection is active. Continuous operation above the specified maximum operating junction temperature may impair device reliability.

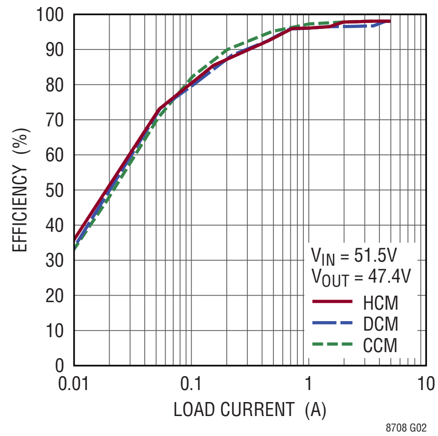
Note 8: Do not force voltage or current into these pins.

TYPICAL PERFORMANCE CHARACTERISTICS

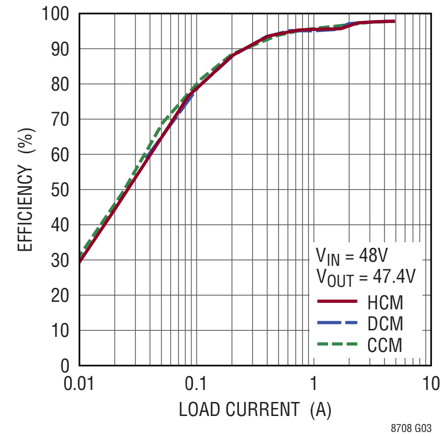
Efficiency vs Output Current (Boost Region – Page 59)



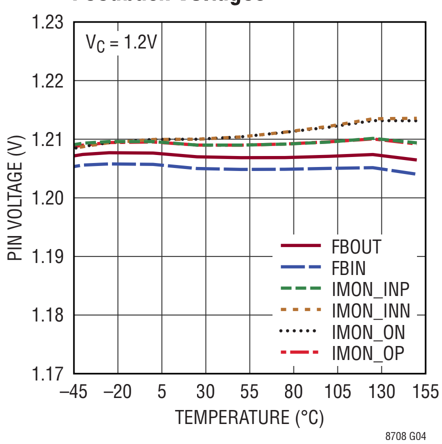
Efficiency vs Output Current (Buck Region – Page 59)



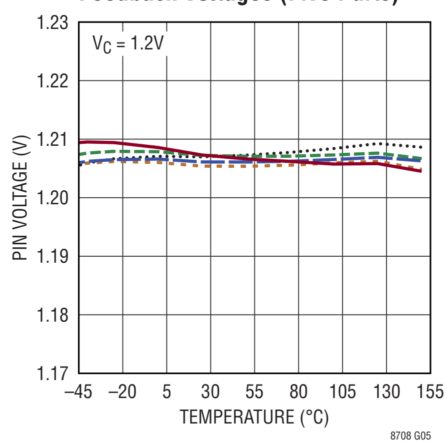
Efficiency vs Output Current (Buck–Boost Region – Page 59)



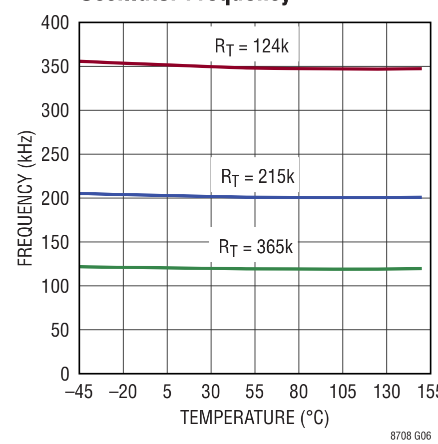
Feedback Voltages



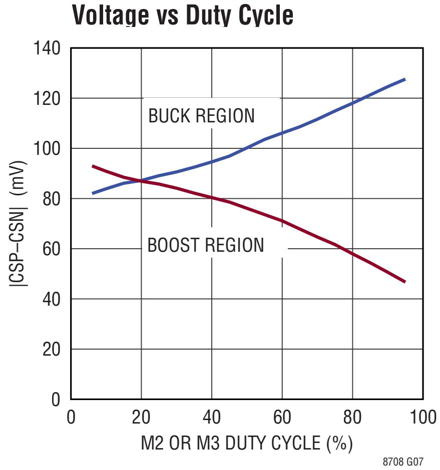
Feedback Voltages (Five Parts)



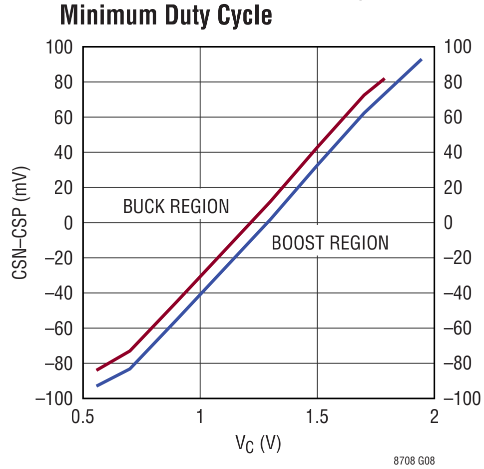
Oscillator Frequency



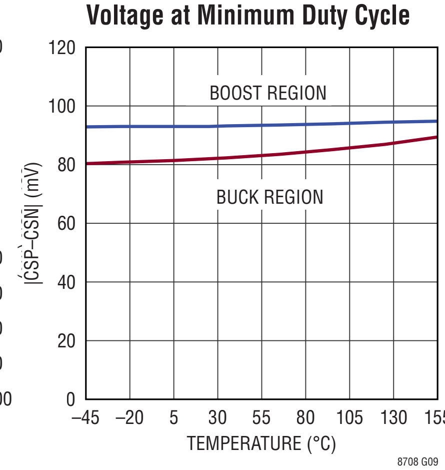
Maximum Inductor Current Sense Voltage vs Duty Cycle



Inductor Current Sense Voltage at Minimum Duty Cycle

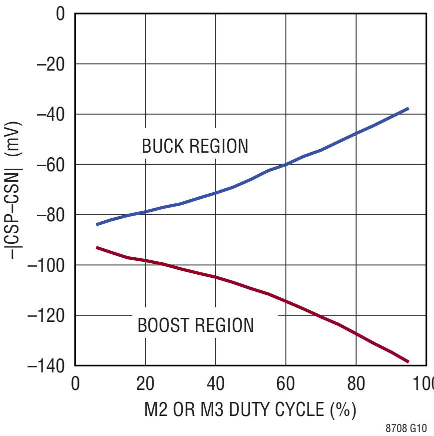


Maximum Inductor Current Sense Voltage at Minimum Duty Cycle

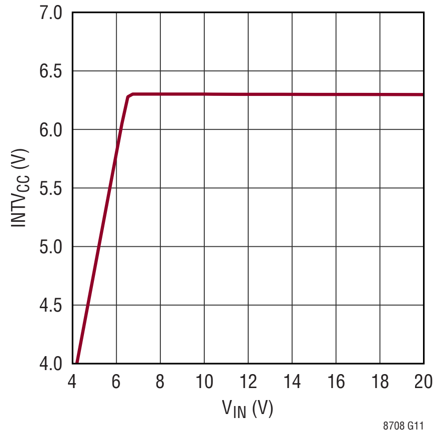


TYPICAL PERFORMANCE CHARACTERISTICS

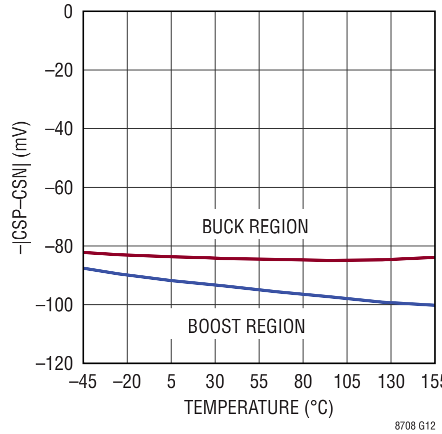
Minimum Inductor Current Sense Voltage vs Duty Cycle



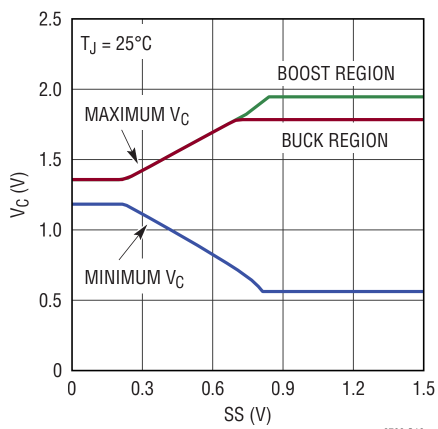
$INTV_{CC}$ Line Regulation ($EXTV_{CC}$ = 0V)



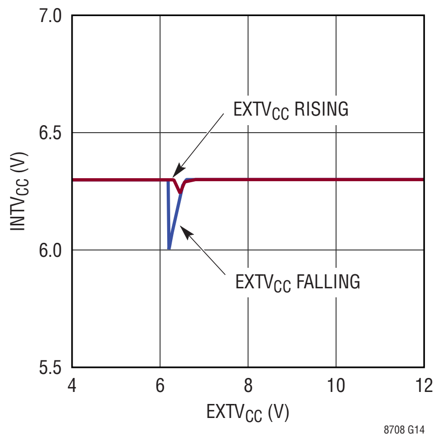
Minimum Inductor Current Sense Voltage at Minimum Duty Cycle



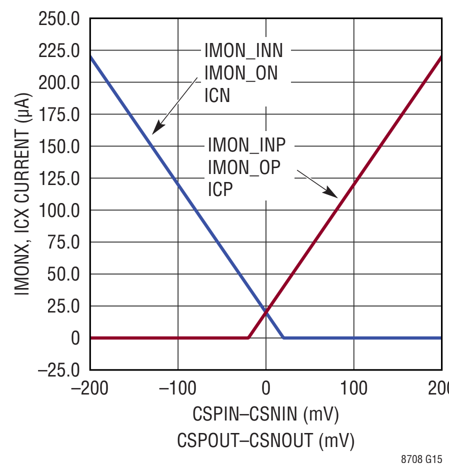
Maximum and Minimum V_C vs SS



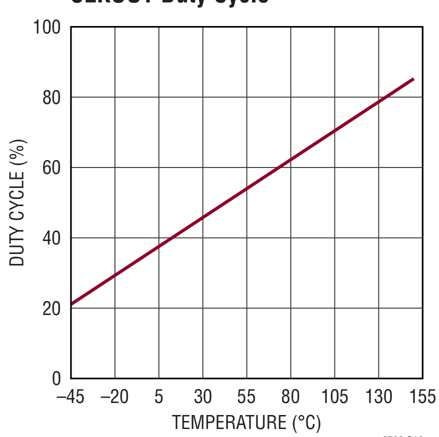
$INTV_{CC}$ Line Regulation (V_{IN} = 12V)



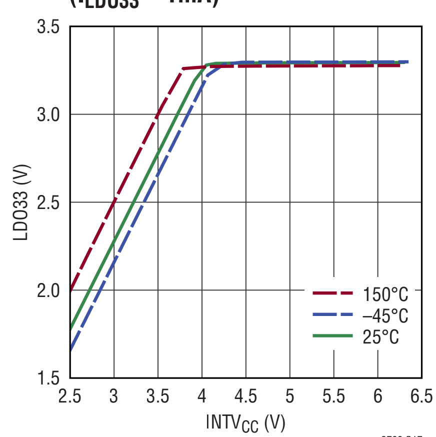
IMONx, ICx Output Current



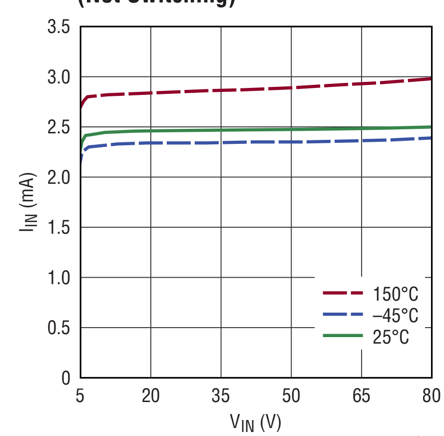
CLKOUT Duty Cycle



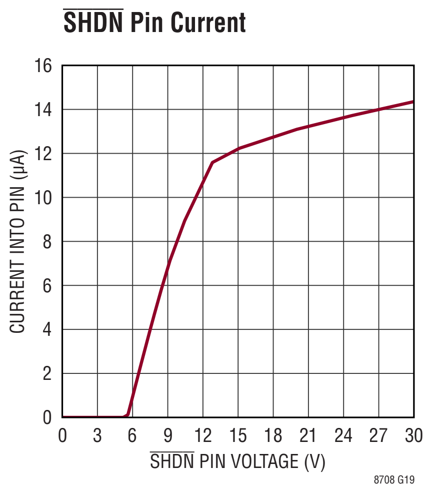
LDO33 Pin Regulation (I_{LDO33} = 1mA)

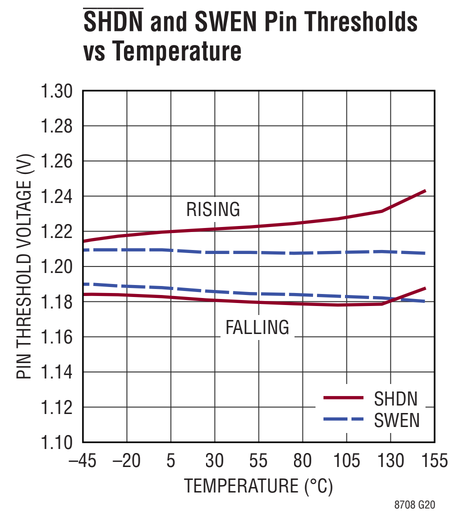


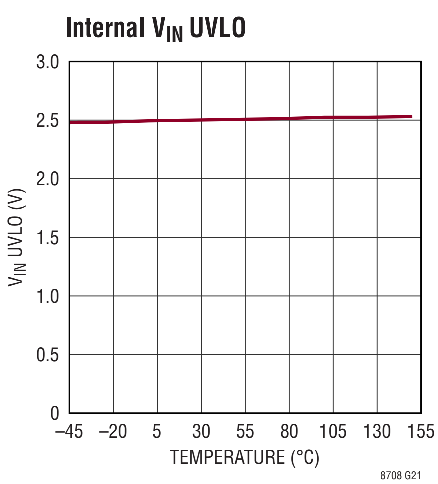
V_{IN} Supply Current vs Voltage (Not Switching)

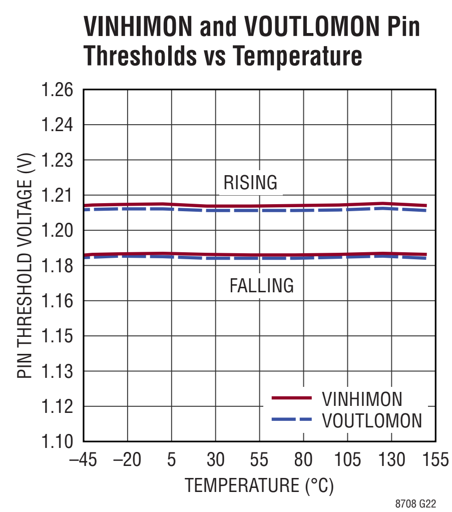


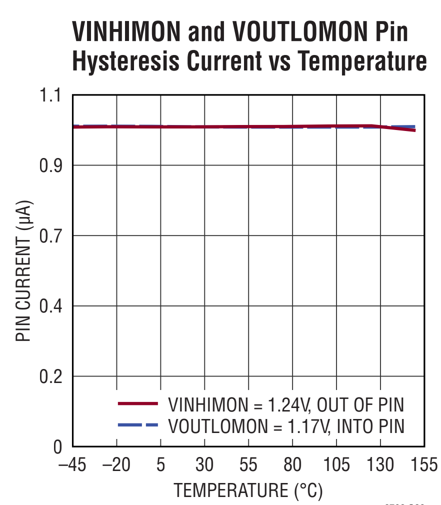
TYPICAL PERFORMANCE CHARACTERISTICS





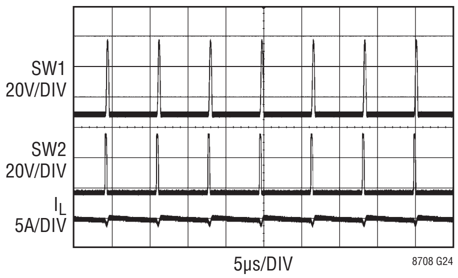






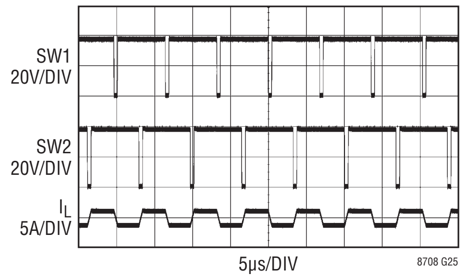
TYPICAL PERFORMANCE CHARACTERISTICS

Discontinuous Mode (Page 59)



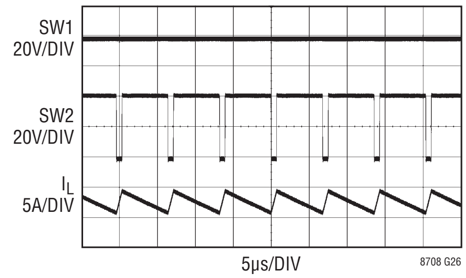
V_{BAT} = 38V
V_{LOAD} = 47.4V

Continuous Mode (Page 59)



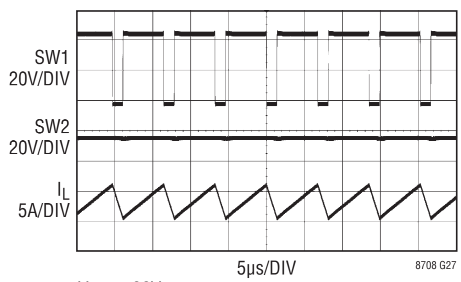
V_{BAT} = 48V
V_{LOAD} = 47.4V

Continuous Mode (Page 59)



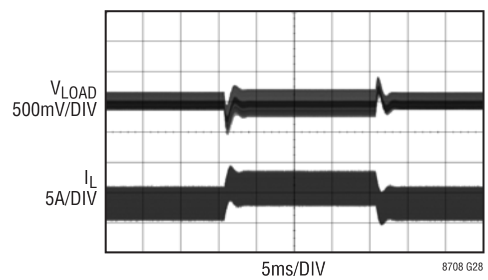
V_{BAT} = 52V
V_{LOAD} = 47.4V

Continuous Mode (Page 59)



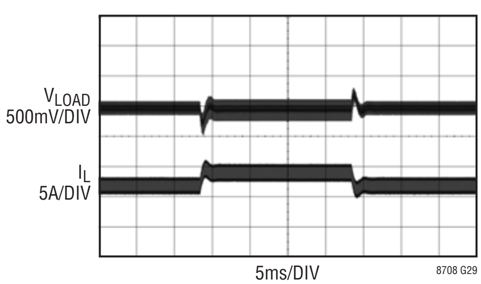
V_{BAT} = 38V
V_{LOAD} = 47.4V

Load Step (Page 59)



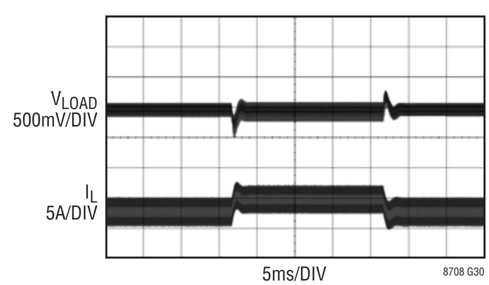
V_{BAT} = 38V
V_{LOAD} = 47.4V
LOAD STEP = 2A TO 4A

Load Step (Page 59)



V_{BAT} = 52V
V_{LOAD} = 47.4V
LOAD STEP = 2A TO 4A

Load Step (Page 59)



V_{BAT} = 48V
V_{LOAD} = 47.4V
LOAD STEP = 2A TO 4A

PIN FUNCTIONS

CLKOUT (Pin 1): Clock Output Pin. Use this pin to synchronize one or more compatible switching regulator ICs to the LT8708. CLKOUT toggles at the same frequency as the internal oscillator or as the SYNC pin, but is approximately 180° out of phase. CLKOUT may also be used as a temperature monitor since the CLKOUT duty cycle varies linearly with the part's junction temperature. The CLKOUT pin can drive capacitive loads up to 200pF.

SS (Pin 2): Soft-Start Pin. Place at least 220nF of capacitance here. Upon start-up, this pin will be charged by an internal resistor to 3.3V.

$\overline{\text{SHDN}}$ (Pin 3): Shutdown Pin. Tie high to enable chip. Ground to shut down and reduce quiescent current to a minimum. Don't float this pin.

CSN (Pin 4): The (–) Input to the Inductor Current Sense and DCM Detect Comparator.

CSP (Pin 5): The (+) Input to the Inductor Current Sense and DCM Detect Comparator. The V_C pin voltage and built-in offsets between CSP and CSN pins, in conjunction with the R_{SENSE} value, set the inductor current trip threshold.

ICN (Pin 6): Negative V_{OUT} Current Monitor. The current out of this pin is 20μA plus a current proportional to the negative average V_{OUT} current. See the Applications Information section for more information.

DIR (Pin 7): Direction pin when MODE is set for DCM (discontinuous conduction mode) or HCM (hybrid conduction mode) operation. Otherwise this pin is ignored. Connect the pin to GND to process power from the V_{OUT} to V_{IN}. Connect the pin to LDO33 to process power from the V_{IN} to V_{OUT}.

FBIN (Pin 8): V_{IN} Feedback Pin. This pin is connected to the input of error amplifier EA3 and is used to detect and/or regulate low V_{IN} voltage.

FBOUT (Pin 9): V_{OUT} Feedback Pin. This pin is connected to the input of error amplifier EA4 and is used to detect and/or regulate high V_{OUT} voltage.

V_C (Pin 10): Error Amplifier Output Pin. Tie external compensation network to this pin.

IMON_INP (Pin 11): Positive V_{IN} Current Monitor and Limit Pin. The current out of this pin is 20μA plus a current proportional to the positive average V_{IN} current. IMON_INP also connects to error amplifier EA5 and can be used to limit the maximum positive V_{IN} current. See the Applications Information section for more information.

IMON_INN (Pin 12): Negative V_{IN} Current Monitor and Limit Pin. The current out of this pin is 20μA plus a current proportional to the negative average V_{IN} current. IMON_INN also connects to error amplifier EA1 and can be used to limit the maximum negative V_{IN} current. See the Applications Information section for more information.

RT (Pin 13): Timing Resistor Pin. Adjusts the switching frequency. Place a resistor from this pin to ground to set the frequency. Do not float this pin.

SYNC (Pin 14): To synchronize the switching frequency to an outside clock, simply drive this pin with a clock. The high voltage level of the clock needs to exceed 1.3V, and the low level should be less than 0.5V. Drive this pin to less than 0.5V to revert to the internal free-running clock. See the Applications Information section for more information.

BG1, BG2 (Pin 16, Pin 18): Bottom Gate Drive. Drives the gate of the bottom N-channel MOSFETs between ground and $GATEV_{CC}$.

$GATEV_{CC}$ (Pin 17): Power supply for bottom gate drivers. Must be connected to the $INTV_{CC}$ pin. Do not power from any other supply. Locally bypass to GND.

BOOST1, BOOST2 (Pin 24, Pin 19): Boosted Floating Driver Supply. The (+) terminal of the bootstrap capacitor connects here. The BOOST1 pin swings from a diode voltage below $GATEV_{CC}$ up to V_{IN} + $GATEV_{CC}$. The BOOST2 pin swings from a diode voltage below $GATEV_{CC}$ up to V_{OUT} + $GATEV_{CC}$.

TG1, TG2 (Pin 23, Pin 20): Top Gate Drive. Drives the top N-channel MOSFETs with voltage swings equal to $GATEV_{CC}$ superimposed on the switch node voltages.

SW1, SW2 (Pin 22, Pin 21): Switch Nodes. The (–) terminals of the bootstrap capacitors connect here.

PIN FUNCTIONS

$\overline{\text{RVSOFF}}$ (Pin 25): Reverse Conduction Disable Pin. This is an input/output open-drain pin that requires a pull up resistor. Pulling this pin low disables reverse current operation. See the Uni and Bidirectional Conduction section for more information.

VOUTLOMON (Pin 26): V_{OUT} Low Voltage Monitor Pin. Connect a ±1% resistor divider between V_{OUT}, VOUTLOMON and GND to set an undervoltage level on V_{OUT}. When V_{OUT} is lower than this level, reverse conduction is disabled to prevent drawing current from V_{OUT}. See the Applications Information section for more information.

VINHIMON (Pin 27): V_{IN} High Voltage Monitor Pin. Connect a ±1% resistor divider between V_{IN}, VINHIMON and GND in order to set an overvoltage level on V_{IN}. When V_{IN} is higher than this level, reverse conduction is disabled to prevent current flow into V_{IN}. See the Applications Information section for more information.

ICP (Pin 28): Positive V_{OUT} Current Monitor Pin. The current out of this pin is 20μA plus a current proportional to the positive average V_{OUT} current. See the Applications Information section for more information.

$EXTV_{CC}$ (Pin 29): External V_{CC} Input. When $EXTV_{CC}$ exceeds 6.4V (typical), $INTV_{CC}$ will be powered from this pin. When $EXTV_{CC}$ is lower than 6.4V, the $INTV_{CC}$ will be powered from V_{INCHIP}.

CSPOUT (Pin 30): The (+) Input to the V_{OUT} Current Monitor Amplifier. This pin and the CSNOUT pin measure the voltage across the sense resistor, R_{SENSE2}, to provide the V_{OUT} current signals. Connect this pin to V_{OUT} when not in use. See Applications Information section for proper use of this pin.

CSNOUT (Pin 31): The (–) Input to the V_{OUT} Current Monitor Amplifier. Connect this pin to V_{OUT} when not in use. See Applications Information section for proper use of this pin.

CSNIN (Pin 32): The (–) Input to the V_{IN} Current Monitor Amplifier. This pin and the CSPIN pin measure the voltage across the sense resistor, R_{SENSE1}, to provide the V_{IN} current signals. Connect this pin to V_{IN} when not in use. See Applications Information section for proper use of this pin.

CSPIN (Pin 33): The (+) Input to the V_{IN} Current Monitor Amplifier. Connect this pin to V_{IN} when not in use. See Applications Information section for proper use of this pin.

V_{INCHIP} (Pin 34): Main Input Supply Pin for the LT8708. It must be locally bypassed to ground.

$INTV_{CC}$ (Pin 35): 6.3V Regulator Output. Must be connected to the $GATEV_{CC}$ pin. $INTV_{CC}$ is powered from $EXTV_{CC}$ when the $EXTV_{CC}$ voltage is higher than 6.4V, otherwise $INTV_{CC}$ is powered from V_{INCHIP}. Bypass this pin to ground with a minimum 4.7μF ceramic capacitor.

SWEN (Pin 36): Switching Regulator Enable Pin. Tie high through a resistor to enable the switching. Ground to disable switching. This pin is pulled down during shutdown, a thermal lockout or when an internal UVLO (undervoltage lockout) is detected. Don't float this pin. See the Start-Up: SWEN Pin section for more details.

MODE (Pin 37): Conduction Mode Select Pin. The voltage applied to this pin sets the conduction mode of the controller. Apply less than 0.4V to enable continuous conduction mode (CCM). Apply 0.8V to 1.2V to enable the hybrid conduction mode (HCM). Apply 1.6V to 2.0V to enable the discontinuous conduction mode (DCM). Apply more than 2.4V to enable Burst Mode operation.

IMON_OP (Pin 38): Positive V_{OUT} Current Monitor and Limit Pin. The current out of this pin is 20μA plus a current proportional to the positive average V_{OUT} current. IMON_OP also connects to error amplifier EA6 and can be used to limit the maximum positive V_{OUT} current. See the Applications Information section for more information.

IMON_ON (Pin 39): Negative V_{OUT} Current Monitor and Limit Pin. The current out of this pin is 20μA plus a current proportional to the negative average V_{OUT} current. IMON_ON also connects to error amplifier EA2 and can be used to limit the maximum negative V_{OUT} current. See the Applications Information section for more information.

LDO33 (Pin 40): 3.3V Regulator Output. Bypass this pin to ground with a minimum 0.1μF ceramic capacitor.

GND (Pin 15, Exposed Pad Pin 41): Ground. Tie directly to local ground plane.

BLOCK DIAGRAM

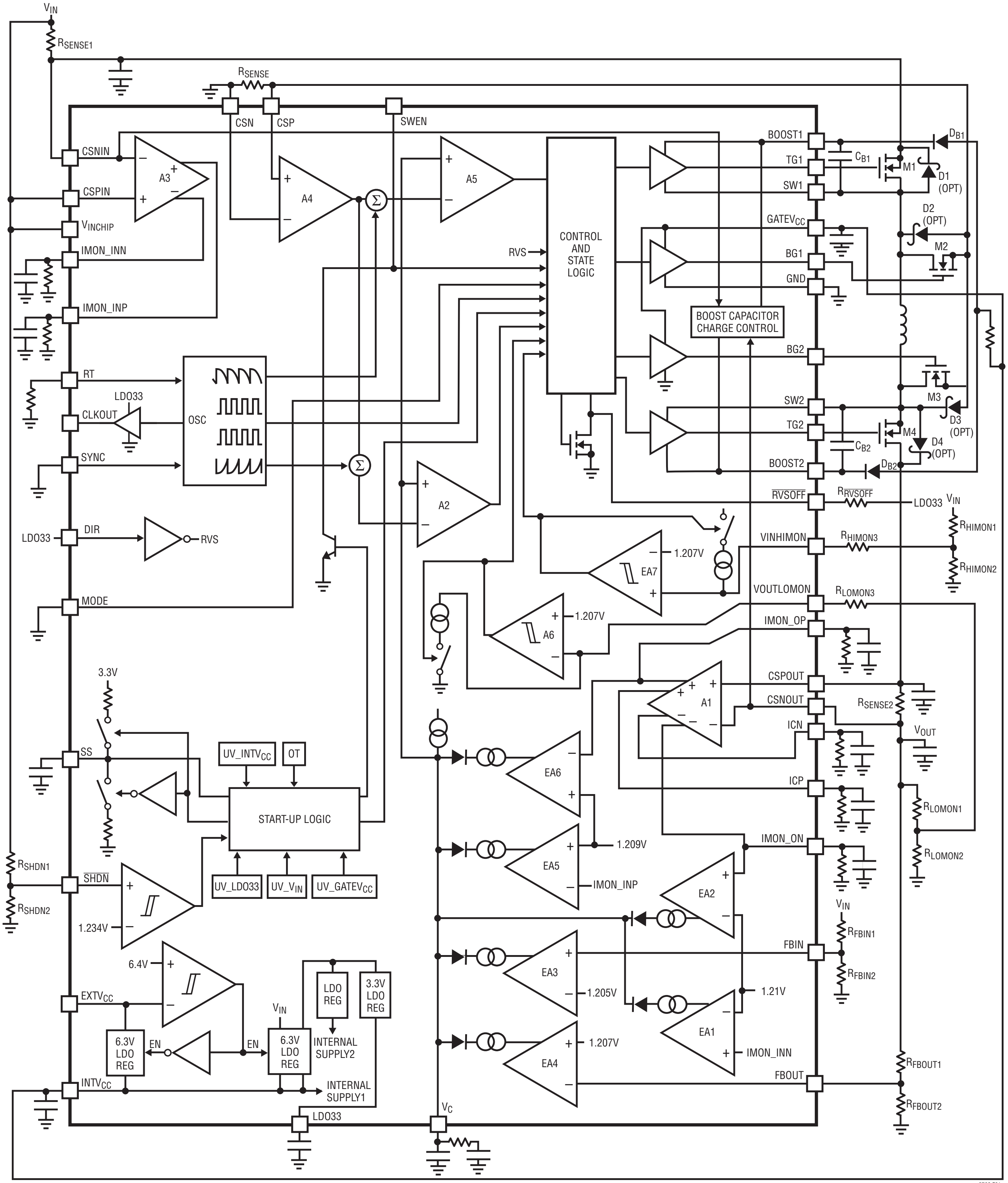


Figure 1. Block Diagram

OPERATION

TYPOGRAPHICAL CONVENTIONS

The LT8708 is a high performance 4-switch buck-boost controller that includes features to facilitate bidirectional current and power flow. Using the LT8708, an application can command power to be delivered from V_{IN} to V_{OUT} or from V_{OUT} to V_{IN} as needed. Some terms, listed below, are used throughout this data sheet in reference to the direction of current and power flow. In order to clarify these direction-based concepts, these terms are defined as follows:

V_{IN} and I_{IN}: The V_{IN} side of circuits drawn in this data sheet will always be on the left. V_{IN} is connected to the SW1 side of the buck-boost inductor through M1. I_{IN} is the V_{IN} current.

V_{OUT} and I_{OUT}: The V_{OUT} side of circuits drawn in this data sheet will always be on the right. V_{OUT} is connected to the SW2 side of the buck-boost inductor through M4. I_{OUT} is the V_{OUT} current.

Supply (Input): Power Source. The power source is most commonly applied to V_{IN}. However, V_{OUT} can be a Supply (or Input) when power is being delivered from V_{OUT} to V_{IN}.

Load (Output): Devices that are consuming the power. The Load is most commonly connected to V_{OUT}. However, V_{IN} can connect to the Load (or Output) when power is being delivered from V_{OUT} to V_{IN}.

Forward Conduction: Current or power flowing from the V_{IN} or SW1 node (or side) to the V_{OUT} or SW2 node (or side) of the circuit. This is generally left to right on schematics.

Reverse Conduction: Current or power flowing from the V_{OUT} or SW2 node (or side) to the V_{IN} or SW1 node (or side) of the circuit. This is general right to left on schematics.

Positive Current: Current that flows from the SW1 side of the buck-boost inductor to the SW2 side. Also refers to current that flows from V_{IN} and/or into V_{OUT}.

Reverse Current: Current that flows from the SW2 side of the buck-boost inductor to the SW1 side. Also refers to current that flows from V_{OUT} and/or into V_{IN}.

Refer to the Block Diagram (Figure 1) when reading the following sections about the operation of the LT8708.

START-UP

Figure 2 illustrates the start-up sequence for the LT8708.

Start-Up: $\overline{SHDN}$ Pin

The master shutdown pin for the chip is $\overline{SHDN}$. When driven below 0.35V (LT8708E, LT8708I) or 0.3V (LT8708H), the chip is disabled (CHIP OFF state) and quiescent current is minimal. Increasing the $\overline{SHDN}$ voltage can increase quiescent current but will not enable the chip until $\overline{SHDN}$ is driven above 1.221V (typical) after which the $INTV_{CC}$ and LDO33 regulators are enabled (SWITCHER OFF 1 state). External devices powered by LDO33 can become active at this time if enough voltage is available on V_{INCHIP} or $EXTV_{CC}$ to raise $INTV_{CC}$, and thus LDO33, to an adequate voltage.

Start-Up: SWEN Pin

The SWEN pin is used to enable the switching regulator after the chip has also been enabled by driving $\overline{SHDN}$ high. SWEN must be pulled high through a resistor to enable the switching regulator. The typical activation threshold is 1.208V as shown in the Electrical Characteristics section. When the SWEN pin voltage is below the activation threshold, the CSP-CSN, CSPIN-CSNIN and CSPOUT-CSNOUT current sense circuits on the chip are disabled.

SWEN has an internal pull-down that is activated when the switching regulator is unable to operate (see CHIP OFF and SWITCHER OFF 1 states in Figure 2). After the chip is able to operate and SWEN is internally pulled down below 0.8V (typical), the internal SWEN pull-down is disabled and start-up can proceed past the SWITCHER OFF1 state.

LDO33 or $INTV_{CC}$ are convenient nodes to pull SWEN up to. Choose a pull-up resistor value that limits the current to less than 200µA when SWEN is pulled low. The SWEN pin can also be digitally driven through a current limiting resistor. Note in the Electrical Characteristics section, the SWEN output low voltage is 0.9V (typical) when $\overline{SHDN}$ is low and/or V_{INCHIP} is unpowered. The SWEN output low is 0.2V when $\overline{SHDN}$ is 3V and V_{INCHIP} is powered.

OPERATION

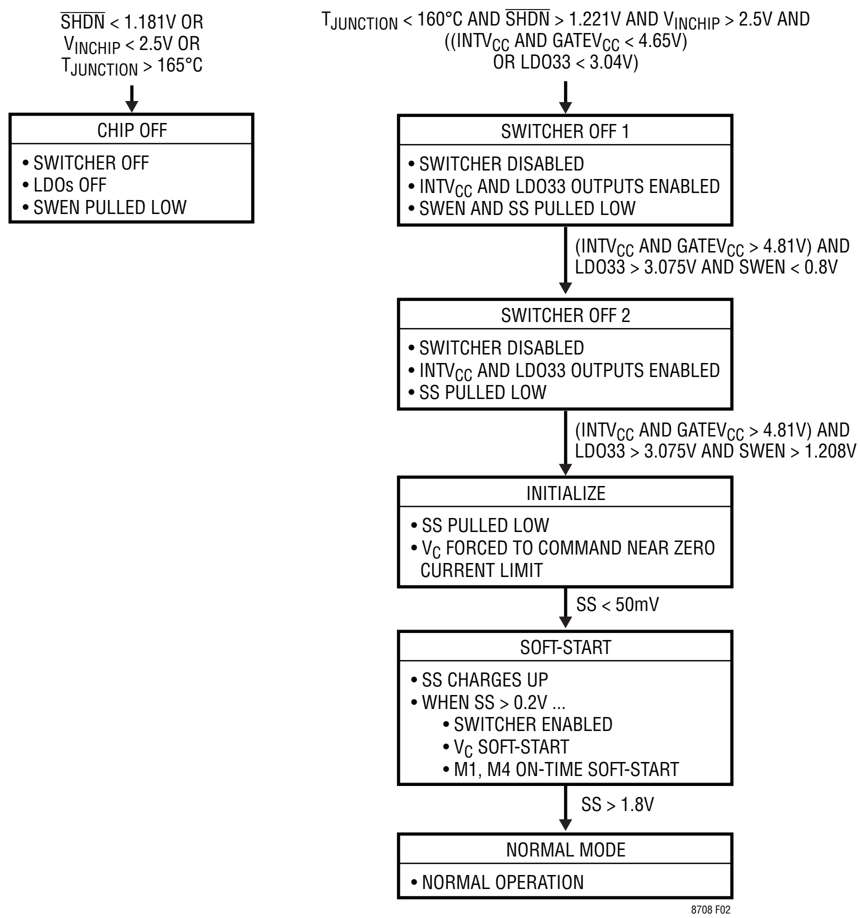


Figure 2. Start-Up Sequence (All Values are Typical)

Start-Up: Soft-Start of Switching Regulator

In the INITIALIZE state, the SS (soft-start) pin is pulled low to prepare for soft-starting the switching regulator. After SS has been discharged to less than 50mV, the SOFT-START state begins. In this state, as SS gradually rises, the soft-start circuitry provides a gradual ramp of V_C and the inductor current in the appropriate direction (refer to the V_C vs SS Voltage graph in the Typical Performance Characteristics section). This prevents abrupt surges of inductor current and helps the output voltage ramp smoothly into regulation. See the Switch Control: Soft-Start section for information about the power switch control during soft-start.

During soft-start, an integrated 180k (typical) resistor pulls SS up to 3.3V. The rising ramp rate of the SS pin voltage is set by this 180k resistor and the external capacitor connected to this pin. When SS reaches 1.8V (typical), the LT8708 exits soft-start and enters normal operation. Typical values for the external soft-start capacitor range from 220nF to 2µF. A minimum of 220nF is recommended.

CONTROL OVERVIEW

The LT8708 is a current mode controller that provides an output voltage above, below or equal to the input voltage. It also provides bidirectional current monitoring and regulation capabilities at both the input and the output.

The ADI proprietary control architecture employs an inductor current-sensing resistor (R_{SENSE}) in buck, boost or buck-boost regions of operation. The inductor current is controlled by the voltage on the V_C pin, which is the combined output of six internal error amplifiers EA1 – EA6. These amplifiers

OPERATION

can be used to limit or regulate their respective voltages or currents as shown in Table 1.

Table 1. Error Amplifiers (EA1 – EA6)

AMPLIFIER NAME	PIN NAME	USED TO LIMIT OR REGULATE
EA1	IMON_INN	Negative I_{IN}
EA2	IMON_ON	Negative I_{OUT}
EA3	FBIN	V_{IN} Voltage
EA4	FBOUT	V_{OUT} Voltage
EA5	IMON_INP	Positive I_{IN}
EA6	IMON_OP	Positive I_{OUT}

The V_C voltage typically has a min-max range of about 1.2V. The maximum V_C voltage commands the most positive inductor current and, thus, commands the most power flow from V_{IN} to V_{OUT}. The minimum V_C voltage commands the most negative inductor current and, thus, commands the most power flow from V_{OUT} to V_{IN}.

In a simple example of V_{OUT} regulation, the FBOUT pin receives the V_{OUT} voltage feedback signal which is compared to the internal reference voltage using EA4. Low V_{OUT} voltage raises V_C and, thus, more current flows into V_{OUT}. Conversely, higher V_{OUT} reduces V_C, thus, reducing the current into V_{OUT} or even drawing current and power from V_{OUT}.

Note that the current and power flow can also be restricted to one direction, as needed, by the selected conduction mode discussed in the Uni and Bidirectional Conduction section.

As mentioned previously, the LT8708 also provides bidirectional current regulation capabilities at both the input and the output. The V_{OUT} current can be regulated or limited in the forward and reverse directions (EA6 and EA2, respectively). The V_{IN} current can also be regulated or limited in the forward direction and reverse directions (EA5 and EA1, respectively).

In a common application, V_{OUT} might be regulated using EA4, while the remaining error amplifiers are monitoring for excessive input or output current or an input undervoltage condition. In other applications, such as a battery backup system, a battery connected to V_{OUT} might be charged with constant current (EA6) to a maximum voltage (EA4) and also reversed, at times, to supply power back to V_{IN} using the other error amplifiers to regulate V_{IN} and limit the maximum current.

POWER SWITCH CONTROL

The following discussions about the power switch control assume that the LT8708 is operating in the continuous conduction mode (see Bidirectional Conduction: CCM). Other conduction modes have slight differences that are discussed later in their respective Conduction sections.

Figure 3 shows a simplified diagram of how the four power switches are connected to the inductor, V_{IN}, V_{OUT} and ground. Figure 4 shows the regions of operation for the LT8708 as a function of V_{OUT} – V_{IN} or switch duty cycle (DC). The power switches are properly controlled so the transfer between modes is continuous.

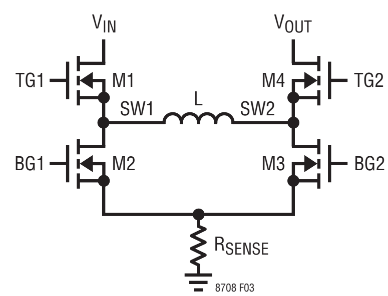


Figure 3. Simplified Diagram of the Buck-Boost Switches

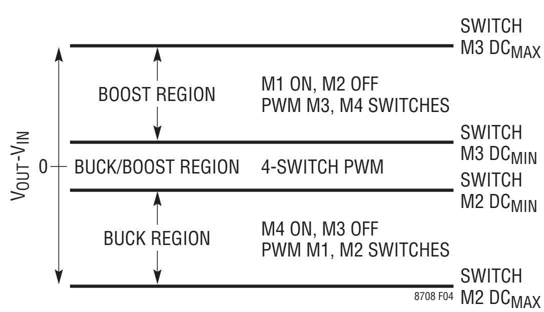


Figure 4. Operating Regions vs V_{OUT} – V_{IN}

OPERATION

Switch Control: Buck Region ($V_{IN} >> V_{OUT}$)

When V_{IN} is significantly higher than V_{OUT}, the part will run in the buck region. In this region M3 is always off and switch M4 is always on. At the start of every cycle, synchronous switch M2 is turned on first. Inductor current is sensed by amplifier A4 while switch M2 is on. A slope compensation ramp is added to the sensed voltage which is then compared by A5 to a reference that is proportional to V_C. After the sensed inductor current falls below the reference, switch M2 is turned off and switch M1 is turned on for the remainder of the cycle. Switches M1 and M2 will alternate, behaving like a typical synchronous buck regulator. Figure 5 shows the switching waveforms in the buck region.

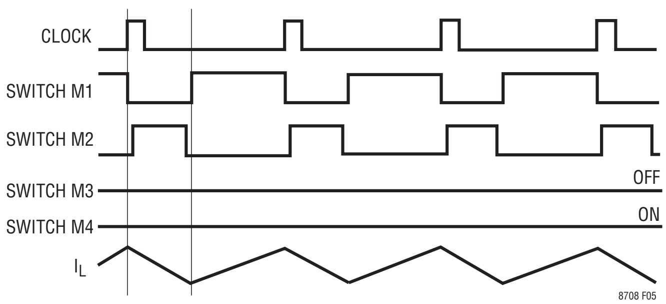


Figure 5. Buck Region ($V_{IN} >> V_{OUT}$)

The part will continue operating in the buck region over a range of switch M2 duty cycles. The duty cycle of switch M2 in the buck region is given by:

$$DC_{(M2,BUCK)} = \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \cdot 100\%$$

As V_{IN} and V_{OUT} get closer to each other, the duty cycle decreases until the minimum duty cycle of the converter, in the buck region, reaches $DC_{(ABSMIN,M2,BUCK)}$. If the duty cycle becomes lower than $DC_{(ABSMIN,M2,BUCK)}$ the part will move to the buck-boost region.

$$DC_{(ABSMIN,M2,BUCK)} \cong t_{ON(M2,MIN)} \cdot f \cdot 100\%$$

where:

$t_{ON(M2,MIN)}$ is the minimum on-time for the synchronous switch in buck operation (200ns typical, see Electrical Characteristics).

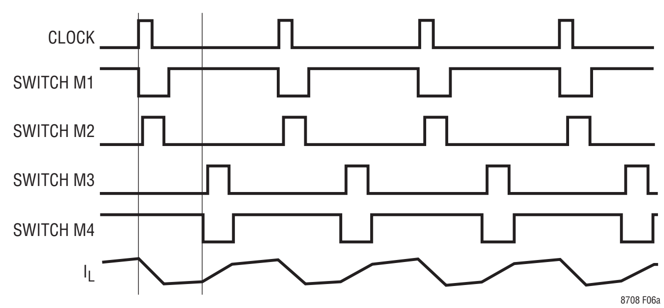
f is the switching frequency.

When V_{IN} is much higher than V_{OUT}, the duty cycle of switch M2 will increase, causing the M2 switch off-time to decrease. The M2 switch off-time should be kept above 230ns (typical, see Electrical Characteristics) to maintain steady-state operation and avoid duty cycle jitter, increased output ripple and reduction in maximum output current.

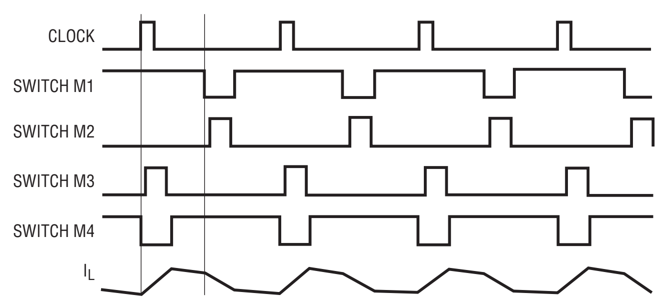
Switch Control: Buck-Boost ($V_{IN} \cong V_{OUT}$)

When V_{IN} is close to V_{OUT}, the controller operates in the buck-boost region. Figure 6 shows typical waveforms in this region. Every cycle, if the controller starts with switches M2 and M4 turned on, the controller first operates as if in the buck region. When A5 trips, switch M2 is turned off and M1 is turned on until the middle of the clock cycle. Next, switch M4 turns off and M3 turns on. The LT8708 then operates as if in boost mode until A2 trips. Finally, switch M3 turns off and M4 turns on until the end of the cycle.

If the controller starts with switches M1 and M3 turned on, the controller first operates as if in the boost region. When A2 trips, switch M3 is turned off and M4 is turned on until the middle of the clock cycle. Next, switch M1



6(a) Buck-Boost Region ($V_{IN} \geq V_{OUT}$)



6(a) Buck-Boost Region ($V_{IN} \leq V_{OUT}$)

Figure 6. Buck-Boost Region

OPERATION

turns off and M2 turns on. The LT8708 then operates as if in buck mode until A5 trips. Finally, switch M2 turns off and M1 turns on until the end of the cycle.

Switch Control: Boost Region (V_{IN} << V_{OUT})

When V_{OUT} is significantly higher than V_{IN}, the part operates in the boost region. In this region switch M1 is always on and switch M2 is always off. At the start of every cycle, switch M3 is turned on first. Inductor current is sensed by amplifier A4 while switch M3 is on. A slope compensation ramp is added to the sensed voltage which is then compared (A2) to a reference that is proportional to V_C. After the sensed inductor current rises above the reference voltage, switch M3 is turned off and switch M4 is turned on for the remainder of the cycle. Switches M3 and M4 will alternate, behaving like a typical synchronous boost regulator.

The part will continue operating in the boost region over a range of switch M3 duty cycles. The duty cycle of switch M3 in the boost region is given by:

$$DC_{(M3,BOOST)} = \left(1 - \frac{V_{IN}}{V_{OUT}}\right) \cdot 100\%$$

As V_{IN} and V_{OUT} get closer to each other, the duty cycle decreases until the minimum duty cycle of the converter, in the boost region, reaches $DC_{(ABSMIN,M3,BOOST)}$. If the duty cycle becomes lower than $DC_{(ABSMIN,M3,BOOST)}$, the part will move to the buck-boost region.

$$DC_{(ABSMIN,M3,BOOST)} \cong t_{ON(M3,MIN)} \cdot f \cdot 100\%$$

where:

$t_{ON(M3,MIN)}$ is the minimum on-time for the main switch in boost operation (200ns typical, see Electrical Characteristics).

f is the switching frequency.

When V_{OUT} is much higher than V_{IN}, the duty cycle of switch M3 will increase, causing the M3 switch off-time to decrease. The M3 switch off-time should be kept above 230ns (typical, see Electrical Characteristics) to maintain steady-state operation and avoid duty cycle jitter, increased output ripple and reduction in maximum output current.

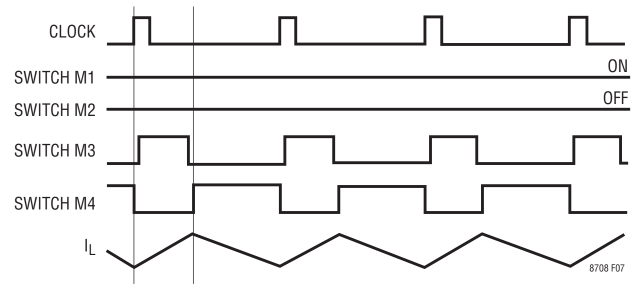


Figure 7. Boost Region (V_{IN} << V_{OUT})

Switch Control: Soft-Start

During soft-start, the LT8708 operates in the same three regions discussed above (buck, buck-boost and boost). However, a few differences in switch control happen during soft-start.

First, M1 and M4 are not turned on simultaneously while SS ramps up to 0.8V (typical). When M1 and M4 would normally both be on, they are instead turned off, leaving all four switches off. After SS rises above 0.8V, during the time when M1 and M4 would normally both be on, they are turned on briefly instead. This brief amount of time increases as SS rises until M1 & M4 are allowed to remain on as long as the normal switching sequence requires.

Second, M2 and M3 will occasionally turn on together for one cycle to refresh both boost capacitors. This refresh cycle happens because M1 and M4 switch more frequently during soft-start than in normal operation. As such, the Boost Capacitor Charge Control block (see Figure 1) cannot always keep the boost capacitors charged. M2 and M3 are turned on when either BOOSTx-SWx voltage drops below 5V (typical). Note that during the refresh cycle, the inductor current slope is nearly zero, thus the boost capacitors can be refreshed without much disturbance to the ongoing switching operations.

UNI AND BIDIRECTIONAL CONDUCTION

The LT8708 has one bidirectional and three unidirectional current conduction modes, primarily selected by the MODE pin. The bidirectional mode (CCM: continuous conduction mode) allows current and power to flow from V_{IN} to V_{OUT}, or vice versa, under control of the V_C pin. The unidirectional

OPERATION

modes (DCM: discontinuous conduction mode, HCM: hybrid current mode and Burst Mode operation) only allow current and power to flow in one direction. Unidirectional settings override the V_C pin's attempt to direct current and power opposite to the selected direction.

The DIR pin selects the allowed power direction when using the DCM and HCM unidirectional modes. The Burst Mode operation only operates in the forward direction and is not affected by the DIR pin. In DCM and HCM modes, driving DIR > 1.6V (typical) selects forward operation which only allows power flow from V_{IN} to V_{OUT}. Driving DIR < 1.2V (typical) selects reverse operation which only allows power flow from V_{OUT} to V_{IN}.

Next, a low state on the $\overline{RVSOFF}$ pin inhibits reverse current and power flow. $\overline{RVSOFF}$ is an open-drain pin that requires a pull-up resistor. LDO33 or $INTV_{CC}$ are convenient nodes to pull $\overline{RVSOFF}$ up to. Normally, $\overline{RVSOFF}$ is only pulled low in response to a low V_{OUT} voltage (via the VOUTLOMON comparator) or a high V_{IN} voltage (via the VINHIMON comparator). However, external devices are permitted to pull $\overline{RVSOFF}$ low as needed. More information is available in the VINHIMON, VOUTLOMON and $\overline{RVSOFF}$ section.

Table 2 summarizes selection of the various conduction modes. See the Electrical Characteristics for the voltage thresholds of the DIR, VINHIMON, VOUTLOMON and $\overline{RVSOFF}$ pins.

Table 2. Conduction Configurations

MODE PIN	DIR PIN STATE	$\overline{RVSOFF}$ PIN STATE	CONDUCTION MODE	POSSIBLE DIRECTION
<0.4V	–	Hi	CCM	Forward and Reverse
		Lo	DCM	Forward
0.8V to 1.2V	Hi	–	HCM	Forward
	Lo	Hi		Reverse
		Lo	–	None
1.6V to 2.0V	Hi	–	DCM	Forward
	Lo	Hi		Reverse
		Lo	–	None
>2.4V	–	Hi	Burst Mode Operation	Forward
		Lo	–	None

The conduction configuration can be changed during operation, as needed, with the following restrictions:

1. Before transitioning from MODE = Burst Mode operation to MODE = CCM, the DIR pin must be driven to the Hi (Forward) state.
2. Avoid control pulses on the MODE and DIR pins narrower than 15 LT8708 clock cycles.

   Note: The V_C pin may be railed at the moment the DIR pin or MODE pin changes state. The railed V_C voltage corresponds to zero current in one direction and maximum current in the other. Therefore, if a small value R_{SENSE} resistor is used, the chip may momentarily command high inductor current immediately after the DIR or MODE pin change. An undersized inductor may become saturated in this case. An edge detector on the DIR and/or MODE pin can be used to reset the chip, forcing a soft-start and limiting the initial current. See the 48V to 14V Bidirectional Dual Battery System with FHCM & RHCM in the Typical Applications section as an example.

More details about each of the four conduction modes are provided in the following sub-sections.

Bidirectional Conduction: CCM

The continuous conduction mode allows the inductor current to flow in the forward or reverse direction, depending on the V_C voltage. When CCM is selected, high V_C voltage causes current and power to flow from V_{IN} to V_{OUT} and low V_C voltage causes current and power to flow from V_{OUT} to V_{IN}. At very light load currents the inductor current may ripple positive and negative as the appropriate average current is delivered to the appropriate output.

Unidirectional Conduction: DCM

The discontinuous conduction mode restricts the inductor current so that it can only flow in one direction, positive towards V_{OUT} (Forward DCM) or negative towards V_{IN} (Reverse DCM). The forward/reverse selection is made by driving the DIR pin as desired.

When FDCM is selected, higher V_C voltage increases the power flowing from V_{IN} to V_{OUT}. Lower V_C voltage reduces or stops the flow. When RDCM is selected, lower V_C voltage

OPERATION

increases the power flowing from V_{OUT} into V_{IN}. Higher V_C voltage reduces or stops the flow.

Forward (or reverse) DCM affects the power switches as follows. Under light loading conditions, in FDCM (or RDCM), synchronous switch M4 (or M1) is turned off whenever instantaneous reverse (or forward) current in the inductor is detected. This is to prevent drawing current from V_{OUT} (or V_{IN}) and feeding current into V_{IN} (or V_{OUT}). Under very light loads, the current comparator may also remain tripped for several cycles and force switches M1 (or M2) and M3 (or M4) to stay off for the same number of cycles i.e., skipping pulses. Synchronous switch M2 (or M3) will remain on during the skipped cycles, but since switch M4 (or M1) is off, the inductor current will not reverse directions.

Unidirectional Conduction: HCM

Large inductor current ripple can sometimes result in high power dissipation of the M4 (or M1) junction diode during the FDCM (or RDCM) operation described above. This can happen, for example, when $V_{IN} >> V_{OUT}$ and the average V_{OUT} current is relatively high, but M4 is turned off to block negative components of the AC inductor current. The hybrid current mode (or HCM) is an alternative to DCM that often reduces the maximum M4 (or M1) heating in such cases.

The hybrid current mode is a mixture of the light load DCM operation and CCM operation, but only allows average current flow in one direction. As such, it is possible to have the lower portions of the inductor current ripple flow opposite to the selected direction while the average current remains in the selected direction. The DIR pin is used to select the desired forward (or FHCM) or reverse (or RHCM) direction of average current flow.

HCM works by measuring the average forward V_{OUT} current and the average reverse V_{IN} current indicated on ICN and IMON_INP, respectively. In FHCM (or RHCM), light load is detected when ICN (or IMON_INP) is above 255mV (typical). As a result, M4 (or M1) is turned off to prevent average current flow opposite to the desired direction. Heavy load is detected when ICN (or IMON_INP) is below 205mV (typical). As a result, CCM operation is enabled, allowing M4 (or M1) to turn on and reduce the diode's power dissipation.

NOTE: In FHCM operation connect a 17.4k resistor from ground to the ICN pin, and in RHCM operation, connect a 17.4k resistor from ground to the IMON_INP pin.

Unidirectional Conduction: Burst Mode

In Burst Mode operation, a V_C voltage is set, with about 25mV of hysteresis, below which switching activity is inhibited and above which switching activity is re-enabled. A typical example is when, at light output currents, V_{OUT} rises and forces the V_C pin below the threshold that temporarily inhibits switching. After V_{OUT} drops slightly and V_C rises ~25mV, the switching is resumed, initially in the buck-boost region. Burst Mode operation can increase efficiency at light load currents by eliminating unnecessary switching activity and related power losses. In Burst Mode operation, inductor current is only allowed in the forward direction, regardless of the voltage on the DIR pin. Burst Mode operation handles reverse-current detection similar to forward DCM. The M4 switch is turned off when reverse inductor current is detected.

ERROR AMPLIFIERS

The six internal error amplifiers combine to drive V_C according to Table 3, with the highest priority being at the top.

Table 3. Error Amp Priorities

TYPICAL CONDITION			PURPOSE
if	IMON_INN > 1.21V or	then V_C Rises	to Reduce Negative I_{IN}
	IMON_ON > 1.21V		to Reduce Negative I_{OUT}
else if	FBIN < 1.205V or	then V_C Falls	to Reduce Positive I_{IN} or Increase Negative I_{IN}
	FBOUT > 1.207V or		to Reduce Positive I_{OUT} or Increase Negative I_{OUT}
	IMON_INP > 1.209V or		to Reduce Positive I_{IN}
	IMON_OP > 1.209V		to Reduce Positive I_{OUT}
else		V_C Rises	Default

Note that certain error amplifiers are disabled under the conditions shown in Table 4. A disabled error amplifier is unable to affect V_C and can be treated as if its associated row is removed from Table 3.

OPERATION

Table 4. Automatically Disabled Error Amp Conditions

ERROR AMP	PIN NAME	VOUTLOMON ASSERTED	VINHIMON ASSERTED	RDCM or RHCM –	RDCM or RHCM $\overline{RVSOFF}$ <1.207V
EA1	IMON_INN				4*
EA2	IMON_ON				4*
EA3	FBIN		2*		4*
EA4	FBOUT	1*		3*	4*
EA5	IMON_INP				4*
EA6	IMON_OP				4*

A 1* – 4* indicates that the error amplifier listed for that row is disabled under that column's condition. The purposes of disabling the respective amplifiers are listed below.

1* This improves transient response when VOUTLOMON deasserts.

2* This improves transient response when VINHIMON deasserts.

3* Since power can only transfer from V_{OUT} to V_{IN}, this prevents higher FBOUT/V_{OUT} voltages from interfering with the FBIN/V_{IN} voltage regulation.

4* No switching occurs in this condition. Disabling the error amplifiers improves transient response when resuming switching operation.

Some applications don't require the use of all six error amplifiers. When unused, the respective input pin(s) should be driven so that they don't interfere with the operation of the remaining amplifiers. Use Table 5 as a guide.

Table 5. Disabling Unused Amplifiers

AMPLIFIER NAME	PIN NAME	TIE TO DISABLE	EXAMPLE DISABLED PIN CONNECTION
EA1	IMON_INN	< 0.9V	GND
EA2	IMON_ON		
EA3	FBIN	> 1.5V	LDO33
EA4	FBOUT	< 0.9V	GND
EA5	IMON_INP		
EA6	IMON_OP		

V_{OUT} REGULATION AND SENSING

Two pins, FBOUT and VOUTLOMON, are provided to sense the V_{OUT} voltage and issue the appropriate response to the switching regulator.

V_{OUT}: Regulation

V_{OUT} is regulated, subject to the priorities in Table 3, using a resistor divider between V_{OUT}, FBOUT and ground. FBOUT connects to the EA4 amplifier to drive V_C. When FBOUT rises near or above the EA4 reference (1.207V typical), V_C typically falls, commanding less current into V_{OUT}. The V_{OUT} regulation voltage is given by the equation:

$$V_{OUT} = 1.207V \bullet \left(1+\frac{R_{FBOUT1}}{R_{FBOUT2}}\right)$$

where:

R_{FBOUT1} and R_{FBOUT2} are shown in Figure 1.

V_{OUT}: Above Regulation

When the FBOUT pin and EA4 detect that V_{OUT} is significantly above regulation, V_C typically falls to its minimum voltage. The LT8708 responds to the minimum V_C voltage according to the conduction mode enabled by MODE, DIR and $\overline{RVSOFF}$. If reverse conduction is not allowed (FDCM, FHCM and Burst Mode operation) then switching will stop and current won't be delivered to V_{IN}. If reverse conduction is allowed (CCM, RDCM and RHCM), then current and power will flow from V_{OUT} to V_{IN}.

V_{OUT}: Below Regulation and Undervoltage

When the FBOUT pin and EA4 detect V_{OUT} is below regulation, V_C typically rises. If forward conduction is enabled (CCM, FDCM, FHCM and Burst mode), then current and power will flow from V_{IN} to V_{OUT}.

A resistor divider between V_{OUT}, VOUTLOMON and ground is used to detect V_{OUT} undervoltage. This function prevents reverse conduction, from V_{OUT} to V_{IN}, from drawing V_{OUT} down lower than desired. When undervoltage is detected by VOUTLOMON, $\overline{RVSOFF}$ is pulled low to disable reverse current and power. This function can be used as a UVLO (undervoltage lockout), for example, when a battery or supercapacitor, connected to V_{OUT}, is supplying power to V_{IN}. See the VINHIMON, VOUTLOMON and $\overline{RVSOFF}$ section for more detailed information.

OPERATION

V_{IN} REGULATION AND SENSING

Two pins, FBIN and VINHIMON, are provided to sense the V_{IN} voltage and issue the appropriate response to the switching regulator.

V_{IN}: Regulation

Subject to the priorities in Table 3, a resistor divider between V_{IN}, FBIN and ground can be used to regulate V_{IN} or serve an undervoltage lockout function. A few application examples are as follows:

- For V_{IN} supplies with high source impedance (i.e., a solar panel), V_{IN} regulation can prevent the supply voltage from dropping too low under high V_{OUT} load conditions.
- For V_{IN} supplies with low source impedance (i.e., batteries and voltage supplies), the FBIN pin can be used to stop switching activity when the V_{IN} supply voltage gets too low for proper system operation.
- V_{IN} can also be regulated to a maximum voltage when power is flowing from V_{OUT} to V_{IN}, such as in a battery backup application.

When FBIN falls near or below the EA3 reference (1.205V typical), the V_C voltage falls and reduces current draw from V_{IN}. The V_{IN} regulation voltage is given by the equation:

$$V_{IN} = 1.205V \bullet \left(1 + \frac{R_{FBIN1}}{R_{FBIN2}}\right)$$

where:

R_{FBIN1} and R_{FBIN2} are shown in Figure 1.

V_{IN}: Above Regulation and Overvoltage

When the FBIN pin and EA3 detect V_{IN} is above regulation, V_C is allowed to rise. If forward conduction is enabled (CCM, FDCM, FHCM and Burst Mode operation), then current and power can flow from V_{IN} to V_{OUT}. If only reverse conduction is enabled (RDCM and RHCM), then switching will stop and current won't be delivered into V_{IN}. NOTE: This above-regulation condition is required to allow forward conduction in an application.

A resistor divider between V_{IN}, VINHIMON and ground is used to detect V_{IN} overvoltage. This function prevents reverse conduction, from V_{OUT} to V_{IN}, from forcing V_{IN} higher than desired. When overvoltage is detected by VINHIMON, $\overline{\text{RVSOFF}}$ is pulled low to disable reverse current and power. This function can be used as an OVLO (over voltage lockout), for example, when a battery, connected to V_{IN}, is being charged from V_{OUT}. See the VINHIMON, VOUTLOMON and $\overline{\text{RVSOFF}}$ section for more detailed information.

V_{IN}: Below Regulation

When the FBIN pin and EA3 detect that V_{IN} is significantly below regulation, V_C may fall to its minimum voltage. The LT8708 responds to the minimum V_C voltage according to the conduction mode enabled by MODE, DIR and $\overline{\text{RVSOFF}}$. If only forward conduction is allowed (FDCM, FHCM and Burst Mode operation) then switching will stop and current won't be drawn from V_{OUT}. If reverse conduction is allowed (CCM, RDCM and RHCM), then current and power will flow from V_{OUT} to V_{IN}.

UVLO functions are available to detect low V_{IN} voltage. These functions are discussed in the Voltage Lockouts section.

CURRENT MONITORING AND LIMITING

Monitoring and Limiting: IMON Pins

The LT8708 can monitor V_{IN} and V_{OUT} current (I_{IN} and I_{OUT}) in both the positive and negative directions. The CSPIN and CSNIN pins connect across a current sense resistor to monitor I_{IN}. External resistors are connected from the IMON_INP and IMON_INN pins to GND. Their resulting voltages are linearly proportional to positive I_{IN} and negative I_{IN} respectively. See amplifier A3 in the Block Diagram.

Similarly, an I_{OUT} sense resistor, measured by CSPOUT and CSNOUT, is used to monitor the V_{OUT} current. External resistors are connected from the IMON_OP and IMON_ON pins to GND. Their resulting voltages are linearly proportional to positive I_{OUT} and negative I_{OUT} respectively. See amplifier A1 in the Block Diagram.

OPERATION

The I_{IN} and I_{OUT} currents can be limited and regulated to independent maximum positive values. When I_{IN} causes IMON_INP to rise near or above 1.209V (typical), EA5 typically causes V_C to pull down and limit/regulate the maximum current. Similarly, when I_{OUT} causes IMON_OP to rise near or above 1.209V (typical), EA6 typically causes V_C to pull down and limit/regulate the maximum current. See Table 3 for error amplifier priorities.

The I_{IN} and I_{OUT} currents can also be limited and regulated to independent maximum negative values. When I_{IN} causes IMON_INN to rise near or above 1.21V (typical), EA1 causes V_C to pull up and limit the maximum current. Similarly, when I_{OUT} causes IMON_ON to rise near or above 1.21V (typical), EA2 causes V_C to pull up and limit the maximum current.

The I_{IN} and I_{OUT} current limits can provide many benefits. They can be used to prevent overloading the input supply, allow for constant-current battery and supercapacitor charging and can also serve as short-circuit protection for constant-voltage regulators. See the Applications Information section for more information about the current monitors and the current regulation and limiting.

Monitoring: ICP and ICN Pins

ICP and ICN are additional current monitor pins with output currents typically equal to those of IMON_OP and IMON_ON, respectively.

In contrast to IMON_OP, ICP is internally pulled to ~0.6V (typical) when V_C is at its minimum and the conduction mode is either RDCM or RHCM. Also, in contrast to IMON_ON, ICN is internally pulled to ~0.6V (typical) when V_C is at its maximum and the conduction mode is FDCM, FHCM or Burst Mode operation.

Always connect a 17.4k resistor from ICP to ground and from ICN to ground.

$INTV_{CC}$/$EXTV_{CC}$/$GATEV_{CC}$/LDO33 POWER

Power for the top and bottom MOSFET drivers, the LDO33 pin and most internal circuitry is derived from the $INTV_{CC}$ pin. $INTV_{CC}$ is regulated to 6.3V (typical) from either the V_{INCHIP} or $EXTV_{CC}$ pin. When the $EXTV_{CC}$ pin is left open or tied to a voltage less than 6.2V (typical), an internal low dropout regulator regulates $INTV_{CC}$ from V_{INCHIP}. If $EXTV_{CC}$ is taken above 6.4V (typical), another low dropout regulator will instead regulate $INTV_{CC}$ from $EXTV_{CC}$. Regulating $INTV_{CC}$ from $EXTV_{CC}$ allows the power to be derived from the lowest supply voltage (highest efficiency) such as the LT8708 switching regulator output (see $INTV_{CC}$ Regulators and $EXTV_{CC}$ Connection in the Applications Information section for more details).

The $GATEV_{CC}$ pin directly powers the bottom MOSFET drivers for switches M2 and M3 (see Figure 3). $GATEV_{CC}$ should always be connected to $INTV_{CC}$ and should not be powered or connected to any other source. Undervoltage lockouts (UVLOs) monitoring $INTV_{CC}$ and $GATEV_{CC}$ disable the switching regulator when the pins are below 4.65V (typical).

The LDO33 pin can provide power to external components such as a microcontroller and/or can provide an accurate bias voltage. Load current is limited to 17.25mA (typical). As long as $\overline{SHDN}$ is high, the LDO33 output is linearly regulated from the $INTV_{CC}$ pin and is not affected by the $INTV_{CC}$ or $GATEV_{CC}$ UVLOs or the SWEN pin voltage. LDO33 remains regulated as long as $\overline{SHDN}$ is high and sufficient voltage is available on $INTV_{CC}$ (typically > 4.0V). An undervoltage lockout monitoring LDO33 will disable the switching regulator when LDO33 is below 3.04V (typical).

CLKOUT AND TEMPERATURE SENSING

The CLKOUT pin toggles at the LT8708's internal clock frequency whether the internal clock is synchronized to an external source or is free-running based on the external R_T resistor. The CLKOUT pin can be used to synchronize other devices to the LT8708's switching frequency. Also, the duty cycle of CLKOUT is proportional to the die temperature and can be used to monitor the die for thermal issues.