

# 带降压和降压 - 升压开关稳压器的线性 USB 电池充电器 LTC3558

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LTC3558 是凌力尔特公司推出的一种带两个开关稳压器的线性通用串行总线电池充电器芯片,它适合于在需要多路电源并由单节锂离子/聚合物电池供电的手持设备中应用。电池充电电流可由单个电阻来编程,最大充电电流达 950mA。在充电过程中,电池状态被监视和控制,内部 4h 的定时器控制充电终止。LTC3558 含有一个电流型降压开关稳压器和一个电压型降压 - 升压稳压器,两个开关稳压器在 2.25MHz 的定频上工作,可以提供 400mA 的输出电流,效率高于 90%。两种开关稳压器输出电压可编程,可用于为微控制器内核、微控制器 I/O、存储器、磁盘驱动器或其他逻辑电路供电。

## 基本结构与引脚功能

LTC3558 采用了尺寸为 3 × 3 × 0.75mm 的 21 引脚 QFN 封装,引脚排列如图 1 所示。

LTC3558 芯片含有一个锂离子电池充电器、一个电流模式降压开关稳压器和一个电压模式降压 - 升压开关稳压器以及两个开关稳压器公用的 0.8V 的基准电压与 2.25MHz 的振荡器,如图 2 所示。表 1 列出了 LTC3558 各个引脚功能。

## 功能与工作原理

LTC3558 的典型应用电路如图 3 所示。事实上,电池充电器可以利用墙上适

配器作为供电源,也可以利用 USB 电源操作,IC 的  $V_{CC}=4.3 \sim 5.5V$ 。

1. 电池充电器只有  $V_{CC}>4V$ ,IC 才会使能。如果  $V_{CC}<4V$ ,或者  $V_{CC}$  降至电池电压的 50mV 之内,充电器将被禁止。

充电器满标度充电电流(即在恒流模式充电电流的 100%)由 IC 引脚 PROG 来设定,其值为  $I_{CHG}=800V/R_{PROG}$ 。如果 IC 引脚 HPWR 被拉至高电平,在恒流充电

时该引脚上的电压则随动至 1V,对应于满标度充电电流。如果引脚 HPWR 为低电平,该引脚上的电压伺服至 0.2V,则对应于满标度电流的 20%(即 0.2C)。无论在何种模式,IC 引脚 BAT 上的电流都可以表示为  $I_{BAT}=(V_{PROG}/R_{PROG}) \times 800$ 。

在充电周期开始时,充电器能探测已深度放电的电池。如果电池电压  $V_{BAT}<2.9V$ ,充电器则用满标度电流的 10%(即 0.1C)

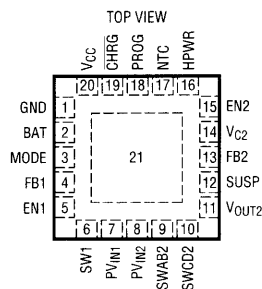


图 1

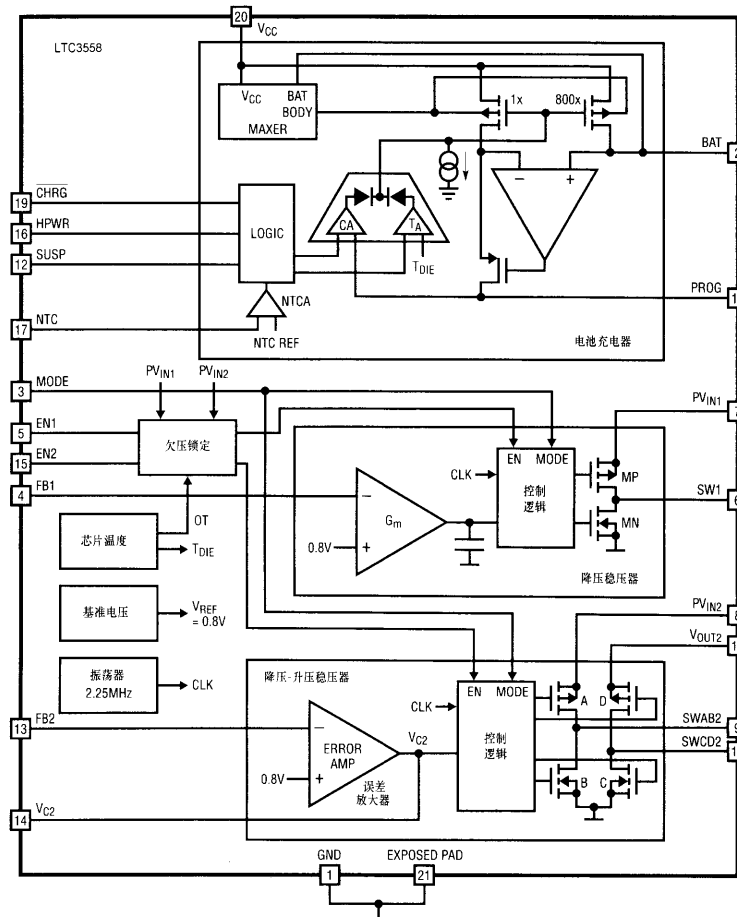


图 2

表 1

引脚号	名称	功能
1	GND	地,该端连接到裸露焊接区
21	Exposed Pad	裸露焊板,它应与 PCB 地焊接在一起
20	Vcc	电池充电器出入电压端
2	BAT	充电电流输出,最终将电池悬浮电压调节到 4.2V
18	PROG	充电电流编程和充电电流监视端
17	NTC	NTC 热敏电阻监测电路输入端
12	SUSP	当该引脚上电压高于 1.2V 时,充电进入暂停模式,并复位终端定时器
16	HPWR	电池充电使能端。当该端上电压高于 1.2V 时,在引脚 BAT 上的输出电流为满标度电流 100%;当该端上电压低于 0.4V 时,充电电流为满标度电流 20%(即 C15)
19	CHRG	开路漏极充电状态输出端
3	MODE	开关稳压器模式选择端。当该引脚问高电平时,两个稳压器工作在突发模式;当该端为低压电平时,降压稳压器在脉冲跳越模式工作,而降压-升压稳压器在定频 PWM 模式
5	EN1	降压变换器使能端,高电平有效
7	PV <sub>IN1</sub>	降压变换器电源输出端,连接该端至 PVcc1 和 BAT 端
4	FB1	降压变换器输出电压经电阻分压器反馈至该端
6	SW1	降压变换器开关节点,连接到电感器
8	PV <sub>IN2</sub>	降压-升压变换器电源输入端,连接到 BAT 和 PV <sub>IN1</sub>
15	EN2	降压-升压变换器使能输入,高电平有效
9	SWAB2	降压-升压变换器开关节点,在该端与 SWCD2 之间连接一个电感器
10	SWCD2	降压-升压变换器开关节点,连接一个电感器至 SWAB2
11	V <sub>OUT2</sub>	降压-升压变换器稳压电压输出,其值在 2.75V 与 5.45V 之间
13	FB2	降压-升压变换器输出电压经电阻分压器反馈至该端
14	Vc2	降压-升压变换器电压补偿节点,它是误差放大器输出

对电池进行涓流充电。如果超过 0.5h 电池电压仍低于 2.9V,充电器则自动终止充电,并锁存不良电池状态。当用一个新电池更换已枯竭的电池后,为使充电器复位,可以断开输入电压,然后再接通。

当 V<sub>BAT</sub>>2.9V 时,充电器则在恒流模式充电。当电池电压接近 4.2V 时,充电电流则减小,充电器则转换到恒压模式充电。在 IC 内 4h 的安全定时器期满后,电池充电则终止。一旦 V<sub>BAT</sub> 降至 4.105V 以下,充电周期则再次开始,安全定时器同

时重新启动。如果芯片温度达到约 105℃,IC 内部热反馈环路将自动减小充电电流,从而可防止 IC 及其周围元件因过热而损坏。

充电器可通过微处理器或在 IC 引脚上连接一个 LED 指示器来指示充电器充电、不充电、电池无反应和电池温度超出范围等 4 种状态中的一种,如表 2 所示。

IC 引脚 N<sub>TC</sub> 上连接一个热敏电阻 R<sub>N<sub>TC</sub></sub>,并将其紧靠电池盒,再附加一个偏置电阻 R<sub>NOM</sub>,可用来检测电池温度(见图 3)。

图 4 为完整的典型 NTC 热敏电阻电路。

R<sub>N<sub>TC</sub></sub> 在 25℃时的电阻值是 R<sub>25</sub>,较低温度(冷态)解扣点时的电阻值为 R<sub>COLD</sub>,较高温度(热态)解扣点时的电阻值为 R<sub>HOT</sub>,根据图 4 可得:  $R_{COLD}/(R_{NOM}+R_{COLD}) \times V_{CC}=0.765V_{CC}$ ;  $R_{HOT}/(R_{NOM}+R_{HOT}) \times V_{CC}=0.349V_{CC}$ 。由上面的等式得到  $R_{COLD}=3.25R_{NOM}$ ;  $R_{HOT}=0.536R_{NOM}$ 。

设 R<sub>COLD</sub> 和 R<sub>HOT</sub> 与 R<sub>25</sub> 之比率分别为是 R<sub>COLD</sub> 和 R<sub>HOT</sub>,并选取 R<sub>NOM</sub>=R<sub>25</sub>,则得到  $R_{COLD}=3.25$ ,  $R_{HOT}=0.536 \approx 0.54$ 。

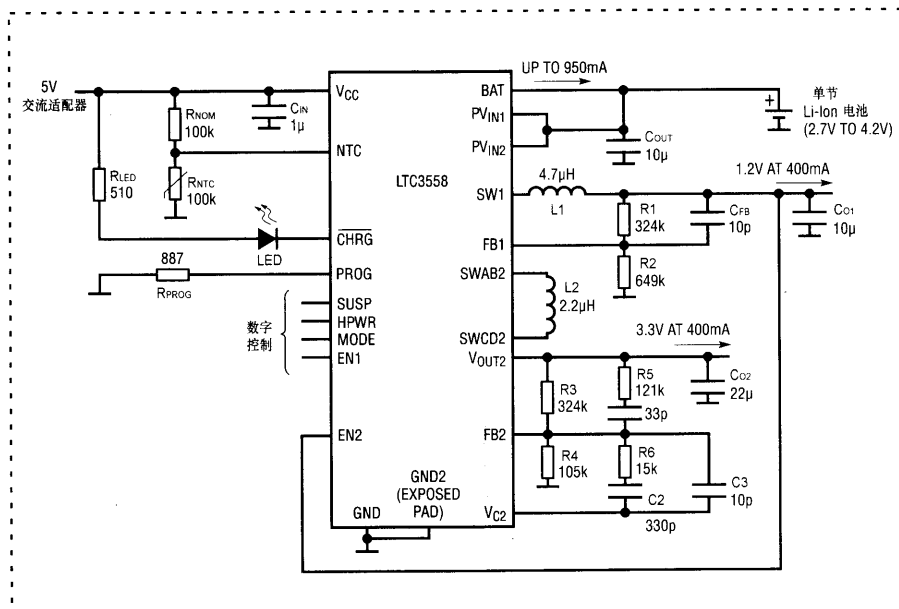


图 3

$R_{NTC}$  选择 Vishay 公司的 NTHS0603NO11-N1003F, 其  $R_{25}=100k\Omega$ 。当其温度升高阻值降至  $0.54$  (即  $54k\Omega$ ) 时, 相应的温度为  $40^{\circ}\text{C}$ , 充电器将暂停充电。当  $R_{NTC}$  阻值增加到  $R_{25}$  的  $3.25$  倍 (即  $325k\Omega$ ) 时, 相应的温度约为  $0^{\circ}\text{C}$ , 充电器也会暂停充电。

2. 电流型降压开关稳压器与降压 - 升压开关稳压器一样, LTC3558 的降压开关稳压器也含有软启动、短路保护和减小辐射 ENI 的开关节点 (SW1) 转换限制电路。电流型降压稳压器在  $2.25\text{MHz}$  的定频上工作, 其输出电压  $V_{O1}$  由  $R1$  和  $R2$  来编程 (见图 3), 其值为  $V_{O1}=0.8\text{V} \times (1+R1/R2)$ , 最大输出电流为  $400\text{mA}$ 。  $R1$  值范围为  $40k\Omega \sim 1\text{M}\Omega$ 。由于选择  $R1=324k\Omega$ ,  $R2=649k\Omega$ ,  $V_{O1}$  值则为  $0.8\text{V} \times (1+324k\Omega/649k\Omega)=1.2\text{V}$ 。电容  $C_{FB}$  能消除反馈电阻与引脚 FB 上电容产生的极点, 并能改善输出电压瞬态响应, 其电容范围为  $2 \sim 22\text{pF}$ 。

利用 IC 引脚 MODE, 可使降压变换器工作于突发模式或脉冲模式或脉冲跳越模式。

在突发模式操作, 能保证降压稳压器在轻载时有最高的效率。在突发模式操作, 降压稳压器自动在定频 PWM 操作与作为负载电流函数的滞后控制之间转换, 在轻载时的开关损耗和噪声降至最小化。输出电容上的电压被充电到稍高于调节点时, 降压稳压器则进入睡眠模式, 其大多数电路掉电。

降压稳压器的峰值电感电流由 IC 引脚 FB1 内部的误差放大器来调节。在非常轻的负载时, 稳压器可以跳过脉冲, 进入脉冲跳越模式, IC 引脚 MODE 应为低电平。

3. 降压 - 升压开关稳压器, 降压 - 升压开关稳压器在输入电压远高于编程输出电压时, 则在降压模式工作; 若输入电压远低于输出电压, 则工作在升压模式。降压 - 升压稳压器也在  $2.25\text{MHz}$  的定频

上操作, 提供直达  $400\text{mA}$  的输出电流。在图 3 中,  $R3/R4$  编程输出电压, 范围为  $2.75 \sim 5.45\text{V}$ , 计算公式为  $V_{O2}=0.8\text{V} \times (1+R3/R4)$ 。当选取  $R3=324k\Omega$  和  $R4=105k\Omega$  时,  $V_{O2} \approx 3.3\text{V}$ 。

降压 - 升压开关稳压器有两种工作模式通过引脚 MODE 可以利用, 这两种模式是 PWM 模式和突发模式。在适度重载时, 选择固定频率 PWM 模式操作; 而在轻载时, 则选择突发模式操作。在突发工作模式, 输出电流被限制在  $50\text{mA}$ 。

误差放大器仅相输入端 (FB2 引脚) 与输出端  $V_{C2}$  之间连接的  $R3$ 、 $R5$ 、 $C1$  和  $R6$ 、 $C2$ 、 $C3$  等为补偿网络。这种 "III 型" 补偿电路有较大的带宽, 能减小启动时输出电压  $V_{O2}$  的过冲, 并允许使用较小的输出滤波电容器。

### 解扣点为 $45^{\circ}\text{C}$ 和 $0^{\circ}\text{C}$ 的应用电路

基于 LTC3558 热和冷解扣点分别为  $45^{\circ}\text{C}$  和  $0^{\circ}\text{C}$  的应用电路如图 5 所示。该电路在没有电池连接到 IC 引脚 BAT 时可以工作。  $R1$  和  $C1$  用作保证充电器的稳定性。降压稳压器输出为  $1.8\text{V}$  ( $@400\text{mA}$ ), 降压 - 升压稳压器输出为  $3.3\text{V}$  ( $@400\text{mA}$ )。

与图 3 比较, 图 4 所示电路不同点之一 NTC 热敏电阻  $R_{NTC}$  又附加了一个偏置电阻  $R_{BO}$ 。  $R_{NTC}$  在  $25^{\circ}\text{C}$  时的电阻值  $R_{25}$  同样为  $100K\Omega$ 。当冷解扣点温度为  $0^{\circ}\text{C}$ 、热解扣点温度为  $45^{\circ}\text{C}$  时, Vishay 公司  $R_{NTC}$

表 2

状态	频率	闪烁频率	占空比数
充电	0Hz	0Hz, 低阻抗, LED 点亮	100%
$I_{BAT} < 0.1\text{C}$	0Hz	0Hz, 高阻抗, LED 熄灭	0%
NTC 热敏电阻故障	35kHz	1.5Hz, LED 闪烁很慢	6.25% ~ 93.75%
不良或损坏电池	35kHz	6.1Hz, LED 闪烁较快	12.5% ~ 87.5%

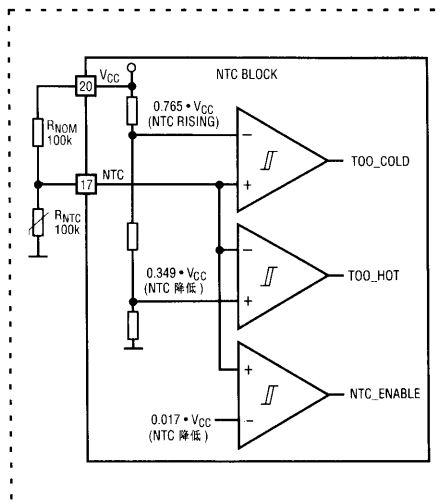
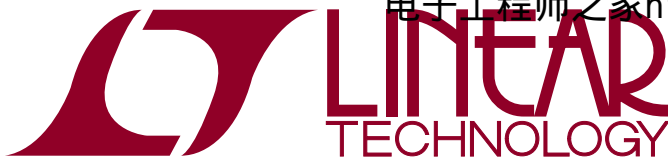


图 4



LTC3558

# Linear USB Battery Charger with Buck and Buck-Boost Regulators

## FEATURES

### Battery Charger

- Standalone USB Charger
- Up to 950mA Charge Current Programmable via Single Resistor
- HPWR Input Selects 20% or 100% of Programmed Charge Current
- NTC Input for Temperature Qualified Charging
- Internal Timer Termination
- Bad Battery Detection

### Switching Regulators (Buck and Buck-Boost)

- Up to 400mA Output Current per Regulator
- 2.25MHz Constant-Frequency Operation
- Power Saving Burst Mode® Operation
- Low Profile, 20-Lead, 3mm × 3mm QFN Package

## APPLICATIONS

- SD/Flash-Based MP3 Players
- Low Power Handheld Applications

## DESCRIPTION

The LTC<sup>®</sup>3558 is a USB battery charger with dual high efficiency switching regulators. The device is ideally suited to power single-cell Li-Ion/Polymer based handheld applications needing multiple supply rails.

Battery charge current is programmed via the PROG pin and the HPWR pin with capability up to 950mA of current at the BAT pin. The  $\overline{\text{CHRG}}$  pin allows battery status to be monitored continuously during the charging process. An internal timer controls charger termination.

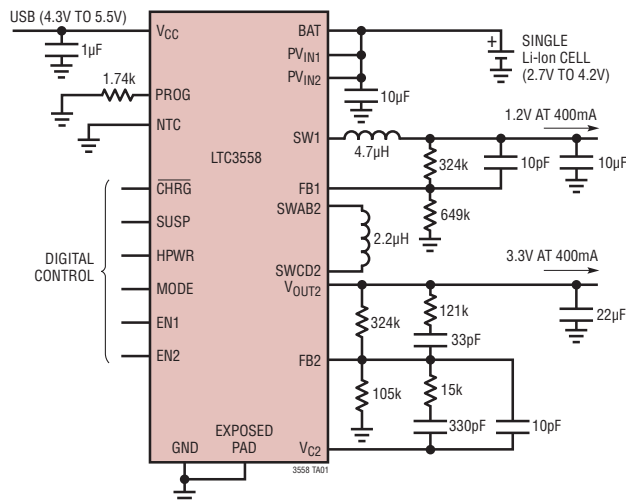
The part includes monolithic synchronous buck and buck-boost regulators that can provide up to 400mA of output current each and operate at efficiencies greater than 90% over the entire Li-Ion/Polymer battery range. The buck-boost regulator can regulate its programmed output voltage at its rated deliverable current over the entire Li-Ion range without drop out, increasing battery runtime.

The LTC3558 is offered in a low profile (0.75mm), thermally enhanced, 20-lead (3mm × 3mm) QFN package.

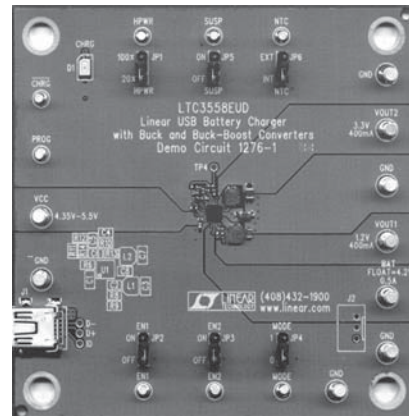
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## TYPICAL APPLICATION

### USB Charger Plus Buck Regulator and Buck-Boost Regulator



### Demo Board



3558f

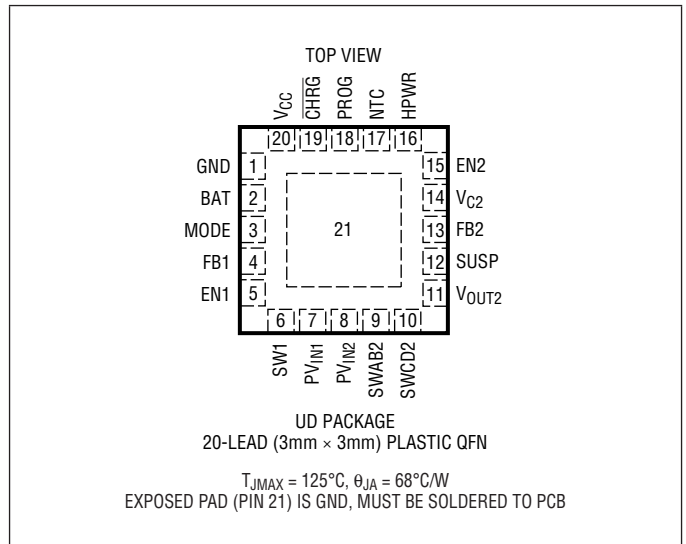
# LTC3558

## ABSOLUTE MAXIMUM RATINGS

(Note 1)

$V_{CC}$ (Transient); $t < 1\text{ms}$ and Duty Cycle $< 1\%$ .....	-0.3V to 7V
$V_{CC}$ (Static) .....	-0.3V to 6V
BAT, CHRG .....	-0.3V to 6V
PROG, SUSP .....	-0.3V to ( $V_{CC} + 0.3\text{V}$ )
HPWR, NTC.....	-0.3V to Max ( $V_{CC}$ , BAT) + 0.3V
PROG Pin Current .....	1.25mA
BAT Pin Current .....	1A
PVIN1, PVIN2 .....	-0.3V to (BAT + 0.3V)
EN1, EN2, MODE, VOUT2 .....	-0.3V to 6V
FB1, SW1 .....	-0.3V to (PVIN1 + 0.3V) or 6V
FB2, VC2, SWAB2 .....	-0.3V to (PVIN2 + 0.3V) or 6V
SWCD2 .....	-0.3V to (VOUT2 + 0.3V) or 6V
ISW1 .....	600mA DC
ISWAB2, ISWCD2, IOUT2 .....	750mA DC
Junction Temperature (Note 2) .....	125°C
Operating Temperature Range (Note 3)....	-40°C to 85°C
Storage Temperature.....	-65°C to 125°C

## PIN CONFIGURATION



## ORDER INFORMATION

LEAD FREE FINISH	TAPE AND REEL	PART MARKING	PACKAGE DESCRIPTION	TEMPERATURE RANGE
LTC3558EUD#PBF	LTC3558EUD#TRPBF	LDGD	20-Lead (3mm × 3mm) Plastic QFN	-40°C to 85°C

Consult LTC Marketing for parts specified with wider operating temperature ranges.

Consult LTC Marketing for information on non-standard lead based finish parts.

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

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

# ELECTRICAL CHARACTERISTICS

The ● denotes specifications that apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ .  $V_{CC} = 5\text{V}$ ,  $BAT = PV_{IN1} = PV_{IN2} = 3.6\text{V}$ ,  $R_{PROG} = 1.74\text{k}$ , unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
<b>Battery Charger</b>						
$V_{CC}$	Input Supply Voltage		● 4.3		5.5	V
$I_{VCC}$	Battery Charger Quiescent Current (Note 4)	Standby Mode, Charge Terminated Suspend Mode, $V_{SUSP} = 5\text{V}$		285 8.5	400 17	$\mu\text{A}$ $\mu\text{A}$
$V_{FLOAT}$	BAT Regulated Output Voltage	$0^\circ\text{C} \leq T_A \leq 85^\circ\text{C}$	4.179 4.165	4.200 4.200	4.221 4.235	V V
$I_{CHG}$	Constant-Current Mode Charge Current	HPWR = 1 HPWR = 0	● 440 84	460 92	500 100	mA mA
$I_{BAT}$	Battery Drain Current	Standby Mode, Charger Terminated, EN1 = EN2 = 0 Shutdown, $V_{CC} < V_{UVLO}$ , BAT = 4.2V, EN1 = EN2 = 0 Suspend Mode, SUSP = 5V, BAT = 4.2V, EN1 = EN2 = 0 $V_{CC} = 0\text{V}$ , EN1 = EN2 = 1, MODE = 1, FB1 = FB2 = 0.85V, $V_{OUT2} = 3.6\text{V}$		-3.5 -2.5 -1.5 -50	-7 -4 -3 -100	$\mu\text{A}$ $\mu\text{A}$ $\mu\text{A}$ $\mu\text{A}$
$V_{UVLO}$	Undervoltage Lockout Threshold	BAT = 3.5V, $V_{CC}$ Rising	3.85	4	4.125	V
$\Delta V_{UVLO}$	Undervoltage Lockout Hysteresis	BAT = 3.5V		200		mV
$V_{DUVLO}$	Differential Undervoltage Lockout Threshold	BAT = 4.05V, ( $V_{CC} - \text{BAT}$ ) Falling	30	50	70	mV
$\Delta V_{DUVLO}$	Differential Undervoltage Lockout Hysteresis	BAT = 4.05V		130		mV
$V_{PROG}$	PROG Pin Servo Voltage	HPWR = 1 HPWR = 0 BAT < $V_{TRKL}$		1.000 0.200 0.100		V V V
$h_{PROG}$	Ratio of $I_{BAT}$ to PROG Pin Current			800		mA/mA
$I_{TRKL}$	Trickle Charge Current	BAT < $V_{TRKL}$	36	46	56	mA
$V_{TRKL}$	Trickle Charge Threshold Voltage	BAT Rising	2.8	2.9	3	V
$\Delta V_{TRKL}$	Trickle Charge Hysteresis Voltage			100		mV
$\Delta V_{RECHRG}$	Recharge Battery Threshold Voltage	Threshold Voltage Relative to $V_{FLOAT}$	-75	-95	-115	mV
$t_{RECHRG}$	Recharge Comparator Filter Time	BAT Falling		1.7		ms
$t_{TERM}$	Safety Timer Termination Period	BAT = $V_{FLOAT}$	3.5	4	4.5	Hour
$t_{BADBAT}$	Bad Battery Termination Time	BAT < $V_{TRKL}$	0.4	0.5	0.6	Hour
$h_{C/10}$	End-of-Charge Indication Current Ratio	(Note 5)	0.085	0.1	0.11	mA/mA
$t_{C/10}$	End-of-Charge Comparator Filter Time	$I_{BAT}$ Falling		2.2		ms
$R_{ON(CHG)}$	Battery Charger Power FET On-Resistance (Between $V_{CC}$ and BAT)	$I_{BAT} = 190\text{mA}$		500		$\text{m}\Omega$
$T_{LIM}$	Junction Temperature in Constant Temperature Mode			105		$^\circ\text{C}$
<b>NTC</b>						
$V_{COLD}$	Cold Temperature Fault Threshold Voltage	Rising NTC Voltage Hysteresis	75	76.5 1.6	78	$\%V_{CC}$ $\%V_{CC}$
$V_{HOT}$	Hot Temperature Fault Threshold Voltage	Falling NTC Voltage Hysteresis	33.4	34.9 1.6	36.4	$\%V_{CC}$ $\%V_{CC}$
$V_{DIS}$	NTC Disable Threshold Voltage	Falling NTC Voltage Hysteresis	● 0.7	1.7 50	2.7	$\%V_{CC}$ mV
$I_{NTC}$	NTC Leakage Current	$V_{NTC} = V_{CC} = 5\text{V}$	-1		1	$\mu\text{A}$

# LTC3558

## ELECTRICAL CHARACTERISTICS

The ● denotes specifications that apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ .  $V_{CC} = 5\text{V}$ ,  $BAT = PV_{IN1} = PV_{IN2} = 3.6\text{V}$ ,  $R_{PROG} = 1.74\text{k}$ , unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
<b>Logic (HPWR, SUSP, CHRG, EN1, EN2, MODE)</b>						
$V_{IL}$	Input Low Voltage	HPWR, SUSP, MODE, EN1, EN2 Pins			0.4	V
$V_{IH}$	Input High Voltage	HPWR, SUSP, MODE, EN1, EN2 Pins	1.2			V
$R_{DN}$	Logic Pin Pull-Down Resistance	HPWR, SUSP Pins	● 1.9	4	6.3	$M\Omega$
$V_{CHRG}$	CHRG Pin Output Low Voltage	$I_{CHRG} = 5\text{mA}$		100	250	mV
$I_{CHRG}$	CHRG Pin Input Current	$BAT = 4.5\text{V}$ , $V_{CHRG} = 5\text{V}$		0	1	$\mu\text{A}$

### Buck Switching Regulator

PV <sub>IN1</sub>	Input Supply Voltage		●	2.7	4.2	V
I <sub>PVIN1</sub>	Pulse Skip Input Current	FB1 = 0.85V, MODE = 0 (Note 6)		220	400	μA
	Burst Mode Current	FB1 = 0.85V, MODE = 1 (Note 6)		35	50	μA
	Shutdown Current	EN1 = 0	●	0	2	μA
	Supply Current in UVLO	PV <sub>IN1</sub> = PV <sub>IN2</sub> = 2V		4	8	μA
PV <sub>IN1</sub> UVLO	PV <sub>IN1</sub> Falling		●	2.30	2.45	V
	PV <sub>IN1</sub> Rising		●		2.55 2.70	V
f <sub>OSC</sub>	Switching Frequency	MODE = 0		1.91	2.25 2.59	MHz
I <sub>LIMSW1</sub>	Peak PMOS Current Limit			550	800 1050	mA
V <sub>FB1</sub>	Feedback Voltage	MODE = 0	●	780	800 820	mV
I <sub>FB1</sub>	FB Input Current	FB1 = 0.85V		−50	50	nA
D <sub>MAX1</sub>	Maximum Duty Cycle	FB1 = 0V	●	100		%
R <sub>PMOS1</sub>	R <sub>DS(ON)</sub> of PMOS	I <sub>SW1</sub> = 100mA		0.65		Ω
R <sub>NMOS1</sub>	R <sub>DS(ON)</sub> of NMOS	I <sub>SW1</sub> = −100mA		0.75		Ω
R <sub>SW1(PD)</sub>	SW Pull-Down in Shutdown			13		kΩ

### Buck-Boost Switching Regulator

PV <sub>IN2</sub>	Input Supply Voltage		●	2.7	4.2	V
I <sub>PVIN2</sub>	PWM Input Current	MODE = 0, I <sub>OUT</sub> = 0A, FB2 = 0.85V (Note 6)		220	400	μA
	Burst Mode Input Current	MODE = 1, I <sub>OUT</sub> = 0A, FB2 = 0.85V (Note 6)		20	30	μA
	Shutdown Current	EN2 = 0, I <sub>OUT</sub> = 0A		0	1	μA
	Supply Current in UVLO	PV <sub>IN1</sub> = PV <sub>IN2</sub> = 2V		4	8	μA
PV <sub>IN2</sub> UVLO	PV <sub>IN2</sub> Falling		●	2.30	2.45	V
	PV <sub>IN2</sub> Rising		●		2.55 2.70	V
V <sub>OUT2</sub> (LOW)	Minimum Regulated Buck-Boost V <sub>OUT</sub>				2.65 2.75	V
V <sub>OUT2</sub> (HIGH)	Maximum Regulated Buck-Boost V <sub>OUT</sub>			5.45	5.60	V
I <sub>LIMF2</sub>	Forward Current Limit (Switch A)	MODE = 0	●	580	700 820	mA
I <sub>PEAK2</sub> (BURST)	Forward Current Limit (Switch A)	MODE = 1	●	180	250 320	mA
I <sub>LIMR2</sub>	Reverse Current Limit (Switch D)	MODE = 0	●	325	450 575	mA
I <sub>ZERO2</sub> (BURST)	Reverse Current Limit (Switch D)	MODE = 1	●	–35	0 35	mA
I <sub>MAX2</sub> (BURST)	Maximum Deliverable Output Current in Burst Mode Operation	2.7V < PV <sub>IN2</sub> < 4.2V 2.75V < V <sub>OUT2</sub> < 5.5V		50		mA
V <sub>FB2</sub>	Feedback Servo Voltage		●	780	800 820	mV
I <sub>FB2</sub>	FB2 Input Current	FB2 = 0.85V		–50	50	nA
f <sub>OSC</sub>	Switching Frequency	MODE = 0		1.91	2.25 2.59	MHz

## ELECTRICAL CHARACTERISTICS

The ● denotes specifications that apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^\circ\text{C}$ .  $V_{CC} = 5\text{V}$ ,  $BAT = PV_{IN1} = PV_{IN2} = 3.6\text{V}$ ,  $R_{PROG} = 1.74\text{k}$ , unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
$R_{DSP(ON)}$	PMOS $R_{DS(ON)}$	$V_{OUT} = 3.6\text{V}$		0.6		$\Omega$
$R_{DSN(ON)}$	NMOS $R_{DS(ON)}$			0.6		$\Omega$
$I_{LEAK(P)}$	PMOS Switch Leakage	Switches A, D	-1		1	$\mu\text{A}$
$I_{LEAK(N)}$	NMOS Switch Leakage	Switches B, C	-1		1	$\mu\text{A}$
$DC_{BUCK(MAX)}$	Maximum Buck Duty Cycle	MODE = 0	● 100			%
$DC_{BOOST(MAX)}$	Maximum Boost Duty Cycle	MODE = 0		75		%
$t_{SS2}$	Soft-Start Time			0.5		ms
$R_{OUT(PD)}$	$V_{OUT}$ Pull-Down in Shutdown			10		$\text{k}\Omega$

**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:**  $T_J$  is calculated from the ambient temperature  $T_A$  and power dissipation  $P_D$  according to the following formula:

$$T_J = T_A + (P_D \cdot \theta_{JA})$$

**Note 3:** The LTC3558E is guaranteed to meet specifications from  $0^\circ\text{C}$  to  $85^\circ\text{C}$ . Specifications over the  $-40^\circ\text{C}$  to  $85^\circ\text{C}$  operating temperature range are assured by design, characterization and correlation with statistical process controls.

**Note 4:**  $V_{CC}$  supply current does not include current through the PROG pin or any current delivered to the BAT pin. Total input current is equal to this specification plus  $1.00125 \cdot I_{BAT}$  where  $I_{BAT}$  is the charge current.

**Note 5:**  $I_{C/10}$  is expressed as a fraction of measured full charge current with indicated PROG resistor.

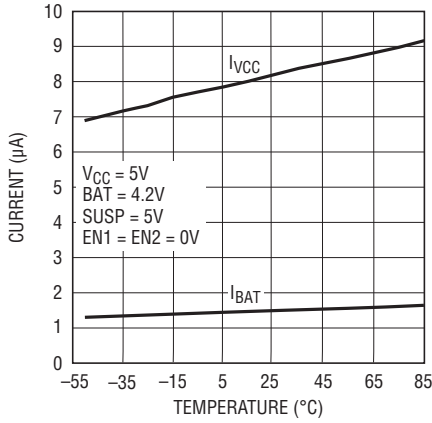
**Note 6:** Dynamic supply current is higher due to the gate charge being delivered at the switching frequency.



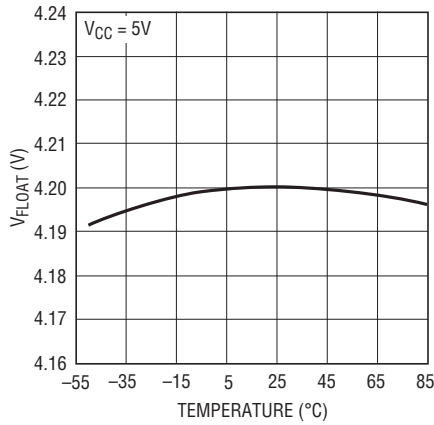
# LTC3558

## TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , unless otherwise noted.

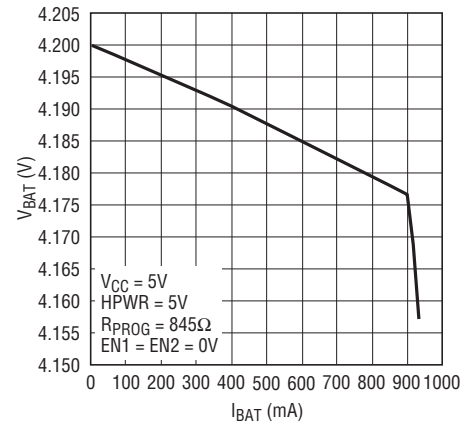
**Suspend State Supply and BAT Currents vs Temperature**



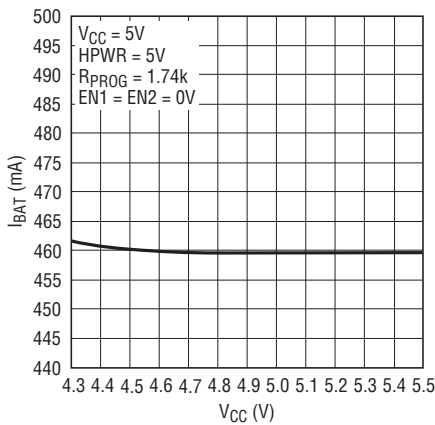
**Battery Regulation (Float) Voltage vs Temperature**



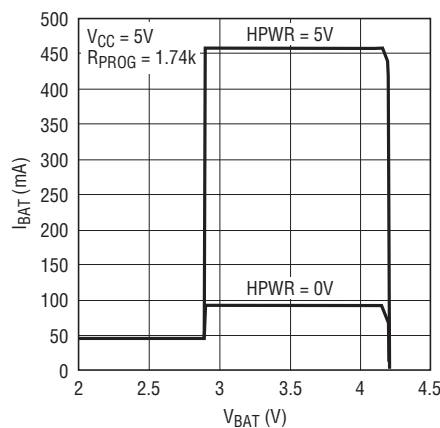
**Battery Regulation (Float) Voltage vs Battery Charge Current, Constant-Voltage Charging**



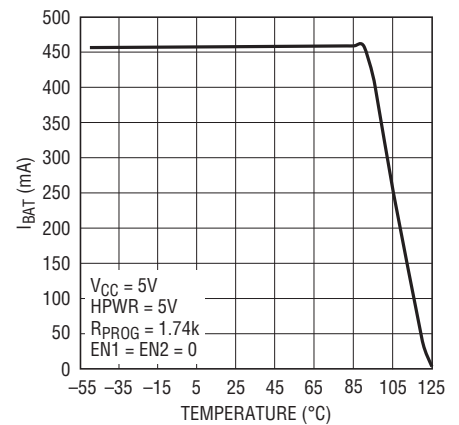
**Battery Charge Current vs Supply Voltage**



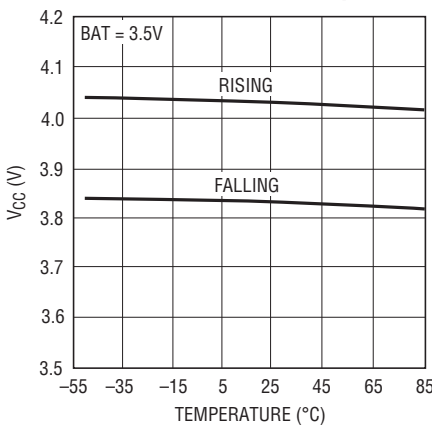
**Battery Charge Current vs Battery Voltage**



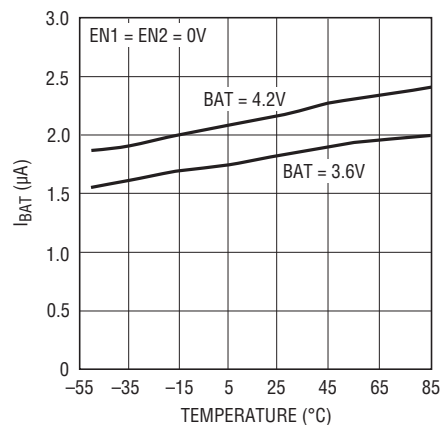
**Battery Charge Current vs Ambient Temperature in Thermal Regulation**



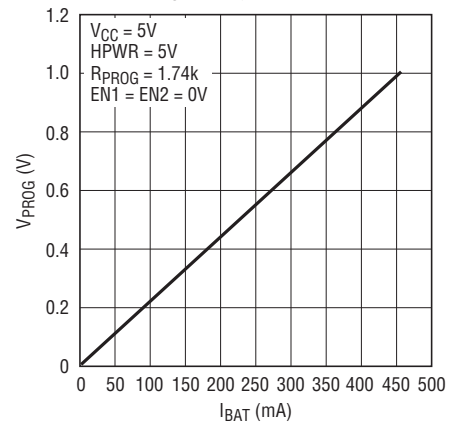
**Battery Charger Undervoltage Lockout Threshold vs Temperature**



**Battery Drain Current in Undervoltage Lockout vs Temperature**

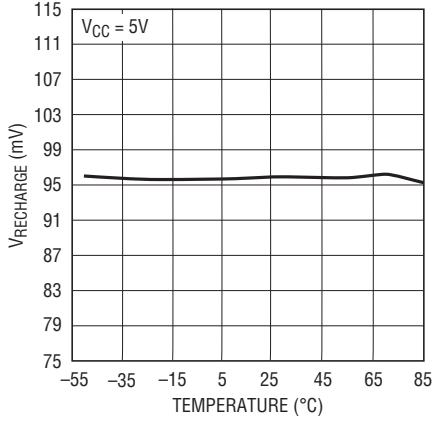


**PROG Voltage vs Battery Charge Current**

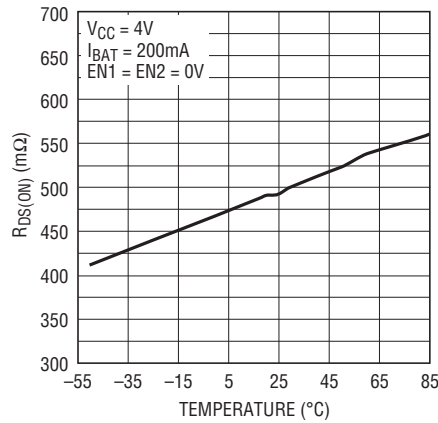


# TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , unless otherwise noted.

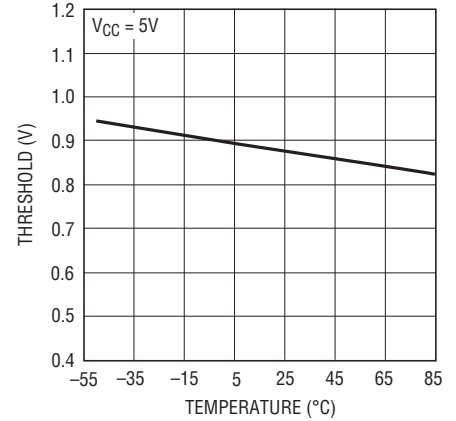
**Recharge Threshold vs Temperature**



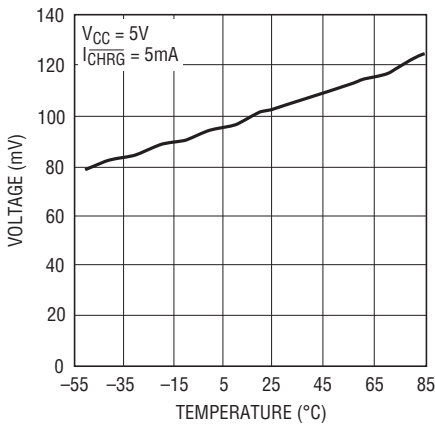
**Battery Charger FET On-Resistance vs Temperature**



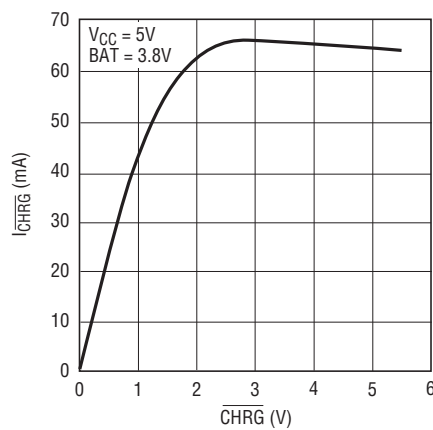
**SUSP/HPWR Pin Rising Thresholds vs Temperature**



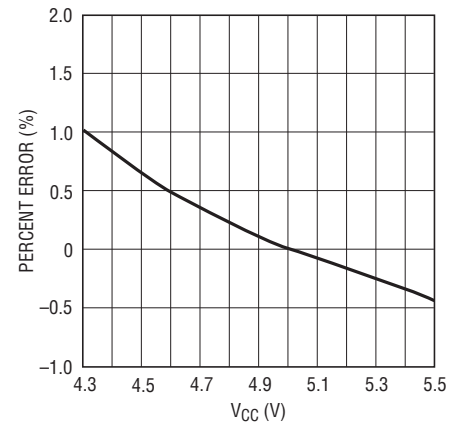
**CHRG Pin Output Low Voltage vs Temperature**



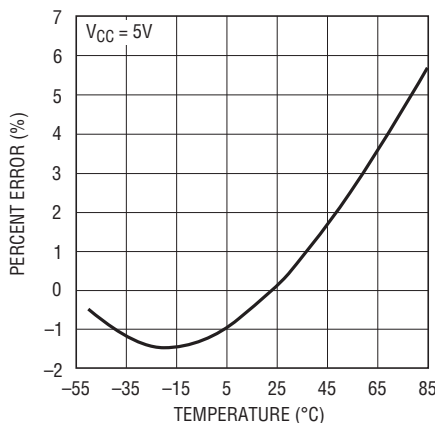
**CHRG Pin I-V Curve**



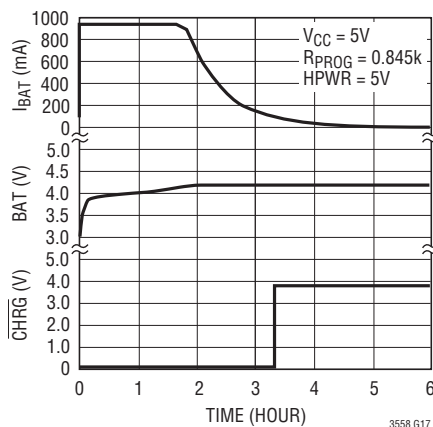
**Timer Accuracy vs Supply Voltage**



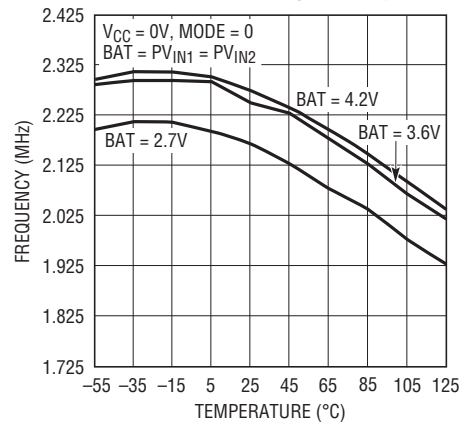
**Timer Accuracy vs Temperature**



**Complete Charge Cycle 2400mAh Battery**



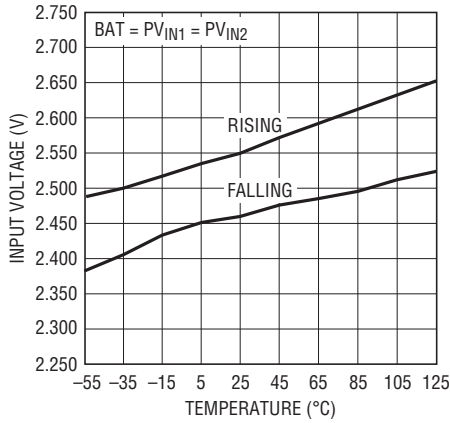
**Buck and Buck-Boost Regulator Switching Frequency vs Temperature**



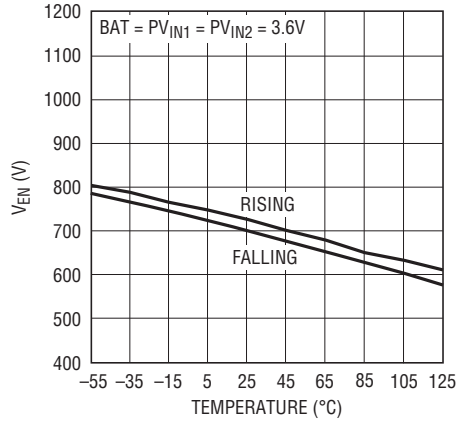
# LTC3558

## TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , unless otherwise noted.

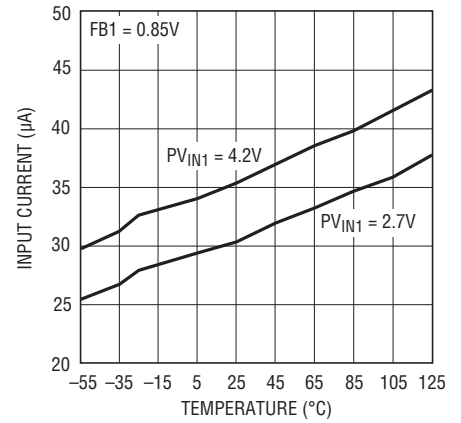
**Buck and Buck-Boost Regulator Undervoltage Thresholds vs Temperature**



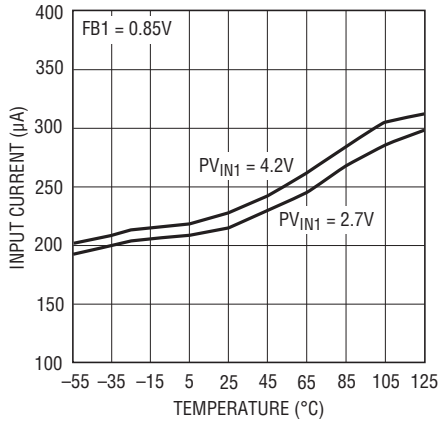
**Buck and Buck-Boost Regulator Enable Thresholds vs Temperature**



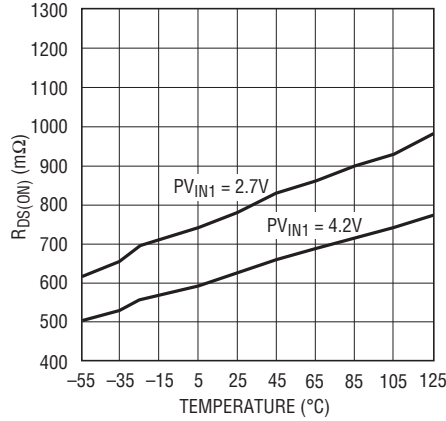
**Buck Regulator Input Current vs Temperature, Burst Mode Operation**



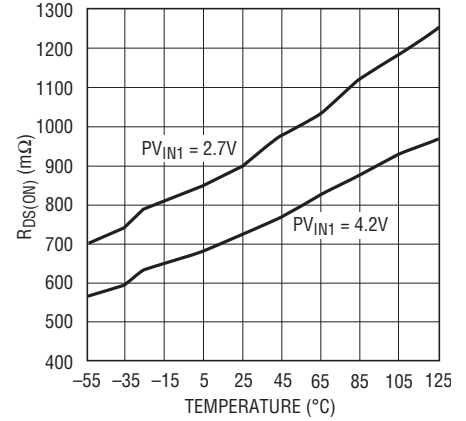
**Buck Regulator Input Current vs Temperature, Pulse Skip Mode**



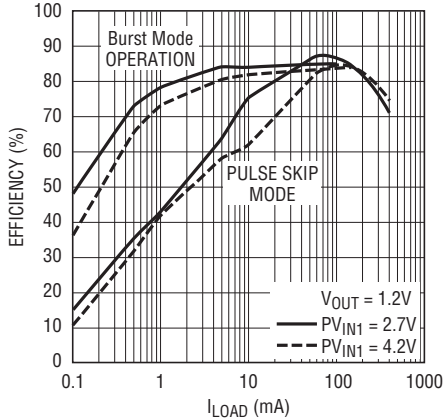
**Buck Regulator PMOS R\_DS(ON) vs Temperature**



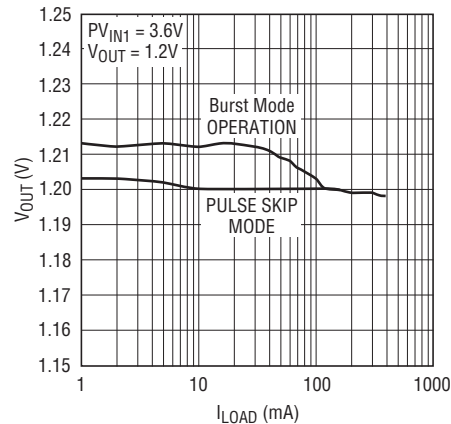
**Buck Regulator NMOS R\_DS(ON) vs Temperature**



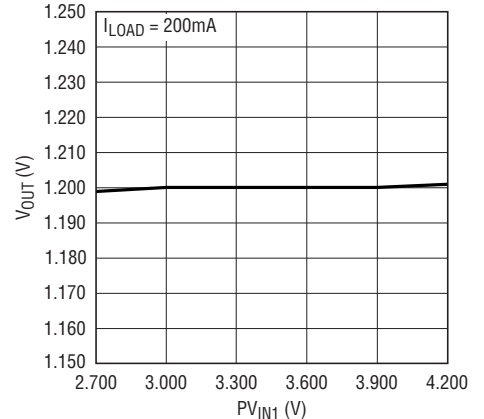
**Buck Regulator Efficiency vs I\_LOAD**



**Buck Regulator Load Regulation**

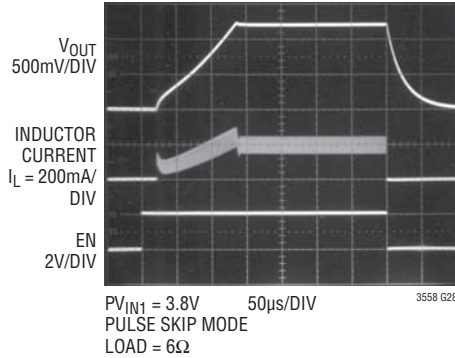


**Buck Regulator Line Regulation**

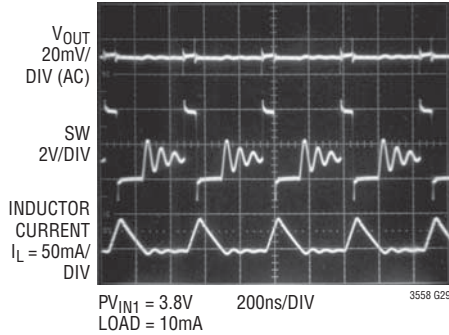


# TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , unless otherwise noted.

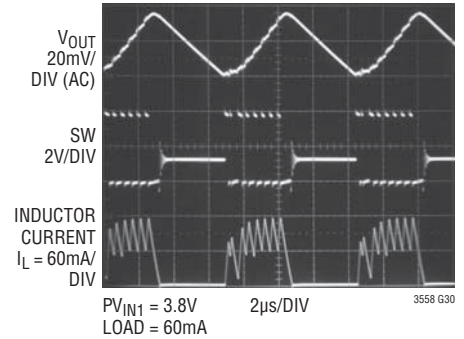
**Buck Regulator Start-Up Transient**



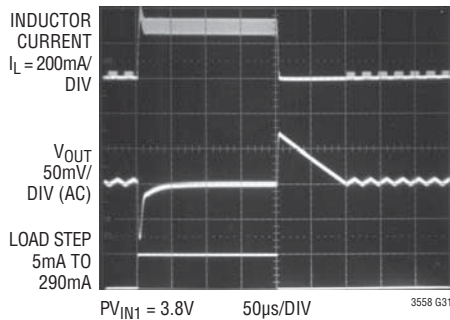
**Buck Regulator  
Pulse Skip Mode Operation**



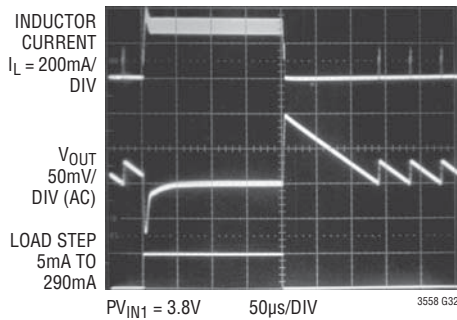
**Buck Regulator  
Burst Mode Operation**



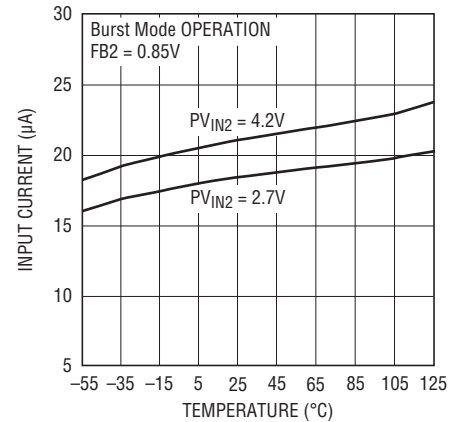
**Buck Regulator Transient  
Response, Pulse Skip Mode**



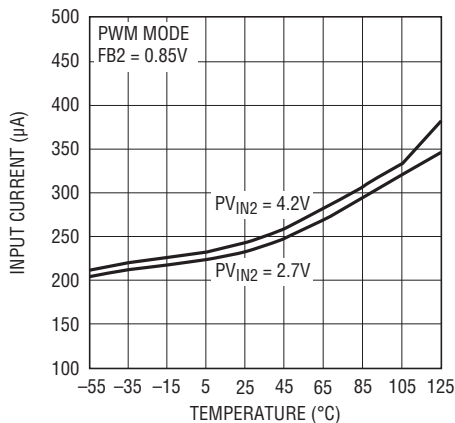
**Buck Regulator Transient  
Response, Burst Mode Operation**



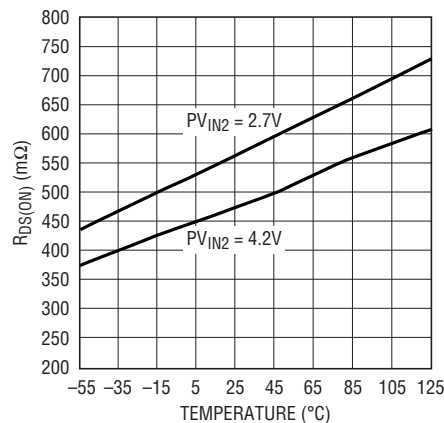
**Buck-Boost Regulator Input  
Current vs Temperature**



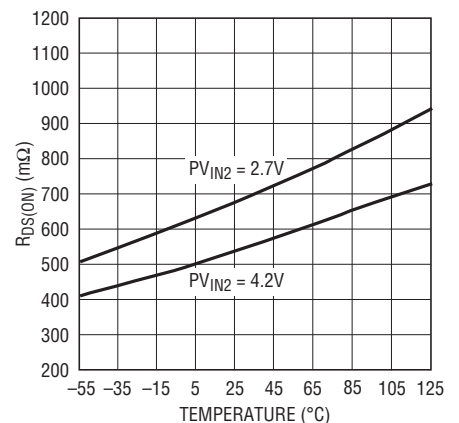
**Buck-Boost Regulator Input  
Current vs Temperature**



**Buck-Boost Regulator PMOS  
 $R_{DS(ON)}$  vs Temperature**



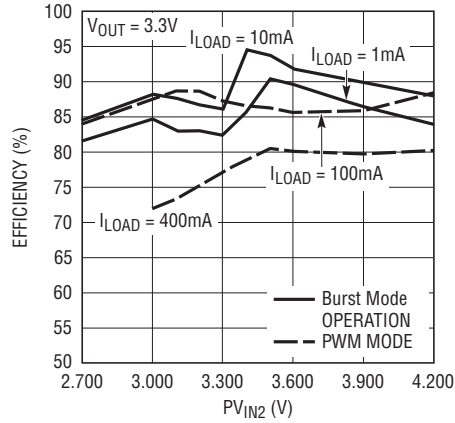
**Buck-Boost Regulator NMOS  
 $R_{DS(ON)}$  vs Temperature**



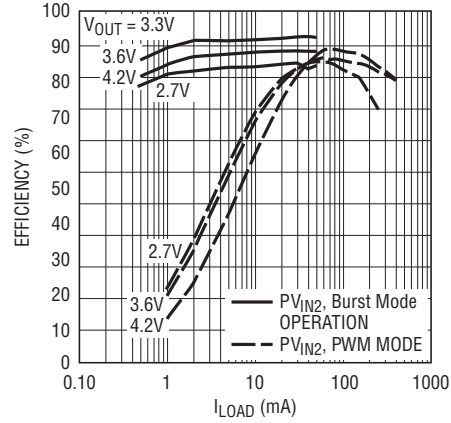
# LTC3558

## TYPICAL PERFORMANCE CHARACTERISTICS $T_A = 25^\circ\text{C}$ , unless otherwise noted.

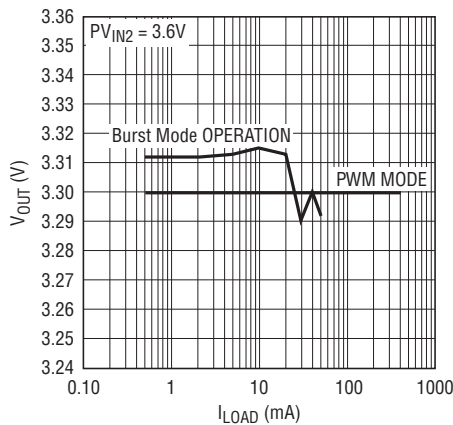
**Buck-Boost Regulator Efficiency vs Input Voltage**



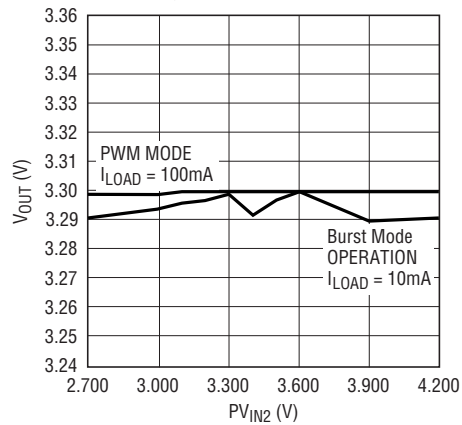
**Buck-Boost Efficiency vs Load Current**



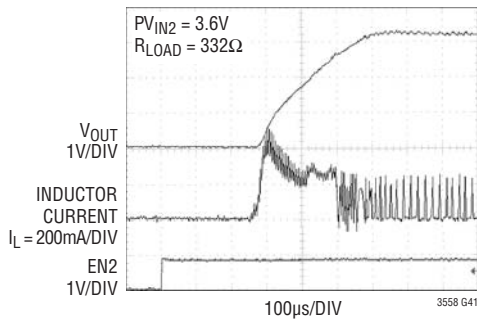
**Buck-Boost Regulator Load Regulation**



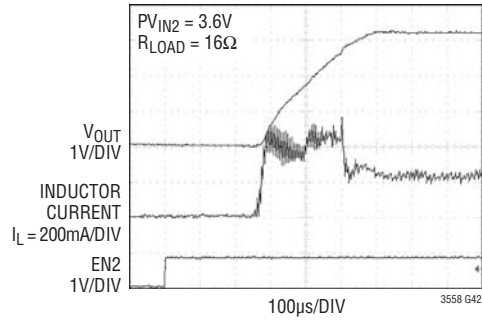
**Buck-Boost Regulator Line Regulation**



**Buck-Boost Regulator Start-Up Transient, Burst Mode Operation**



**Buck-Boost Regulator Start-Up Transient, PWM Mode**



## PIN FUNCTIONS

**GND (Pin 1):** Ground. Connect to Exposed Pad (Pin 21).

**BAT (Pin 2):** Charge Current Output. Provides charge current to the battery and regulates final float voltage to 4.2V.

**MODE (Pin 3):** MODE Pin for Switching Regulators. When held high, both regulators operate in Burst Mode Operation. When held low, the buck regulator operates in pulse skip mode and the buck-boost regulator operates in PWM mode. This pin is a high impedance input; do not float.

**FB1 (Pin 4):** Buck Regulator Feedback Voltage Pin. Receives feedback by a resistor divider connected across the output.

**EN1 (Pin 5):** Enable Input Pin for the Buck Regulator. This pin is a high impedance input; do not float. Active high.

**SW1 (Pin 6):** Buck Regulator Switching Node. External inductor connects to this node.

**PV<sub>IN1</sub> (Pin 7):** Input Supply Pin for Buck Regulator. Connect to BAT and PV<sub>IN2</sub>. A single 10μF input decoupling capacitor to GND is required.

**PV<sub>IN2</sub> (Pin 8):** Input Supply Pin for Buck-Boost Regulator. Connect to BAT and PV<sub>IN1</sub>. A single 10μF input decoupling capacitor to GND is required.

**SWAB2 (Pin 9):** Switch Node for Buck-Boost Regulator Connected to the Internal Power Switches A and B. External inductor connects between this node and SWCD2.

**SWCD2 (Pin 10):** Switch Node for Buck-Boost Regulator Connected to the Internal Power Switches C and D. External inductor connects between this node and SWAB2.

**V<sub>OUT2</sub> (Pin 11):** Regulated Output Voltage for Buck-Boost Regulator.

**SUSP (Pin 12):** Suspend Battery Charging Operation. A voltage greater than 1.2V on this pin puts the battery charger in suspend mode, disables the charger and resets the termination timer. A weak pull-down current is internally applied to this pin to ensure it is low at power-up when the input is not being driven externally.

**FB2 (Pin 13):** Buck-Boost Regulator Feedback Voltage Pin. Receives feedback by a resistor divider connected across the output.

**V<sub>C2</sub> (Pin 14):** Output of the Error Amplifier and Voltage Compensation Node for the Buck-Boost Regulator. External Type I or Type III compensation (to FB2) connects to this pin.

**EN2 (Pin 15):** Enable Input Pin for the Buck-Boost Regulator. This pin is a high impedance input; do not float. Active high.

**HPWR (Pin 16):** High Current Battery Charging Enabled. A voltage greater than 1.2V at this pin programs the BAT pin current at 100% of the maximum programmed charge current. A voltage less than 0.4V sets the BAT pin current to 20% of the maximum programmed charge current. When used with a 1.74k PROG resistor, this pin can toggle between low power and high power modes per USB specification. A weak pull-down current is internally applied to this pin to ensure it is low at power-up when the input is not being driven externally.

**NTC (Pin 17):** Input to the NTC Thermistor Monitoring Circuit. The NTC pin connects to a negative temperature coefficient thermistor which is typically co-packaged with the battery pack to determine if the battery is too hot or too cold to charge. If the battery temperature is out of range, charging is paused until the battery temperature re-enters the valid range. A low drift bias resistor is required from V<sub>CC</sub> to NTC and a thermistor is required from NTC to ground. To disable the NTC function, the NTC pin should be tied to ground.

**PROG (Pin 18):** Charge Current Program and Charge Current Monitor Pin. Charge current is programmed by connecting a resistor from PROG to ground. When charging in constant-current mode, the PROG pin serves to 1V if the HPWR pin is pulled high, or 200mV if the HPWR pin is pulled low. The voltage on this pin always represents the BAT pin current through the following formula:

$$I_{BAT} = \frac{PROG \cdot 800}{R_{PROG}}$$

**CHRG (Pin 19):** Open-Drain Charge Status Output. The CHRG pin indicates the status of the battery charger. Four possible states are represented by CHRG charging, not charging (i.e., the charge current is less than one-tenth

# LTC3558

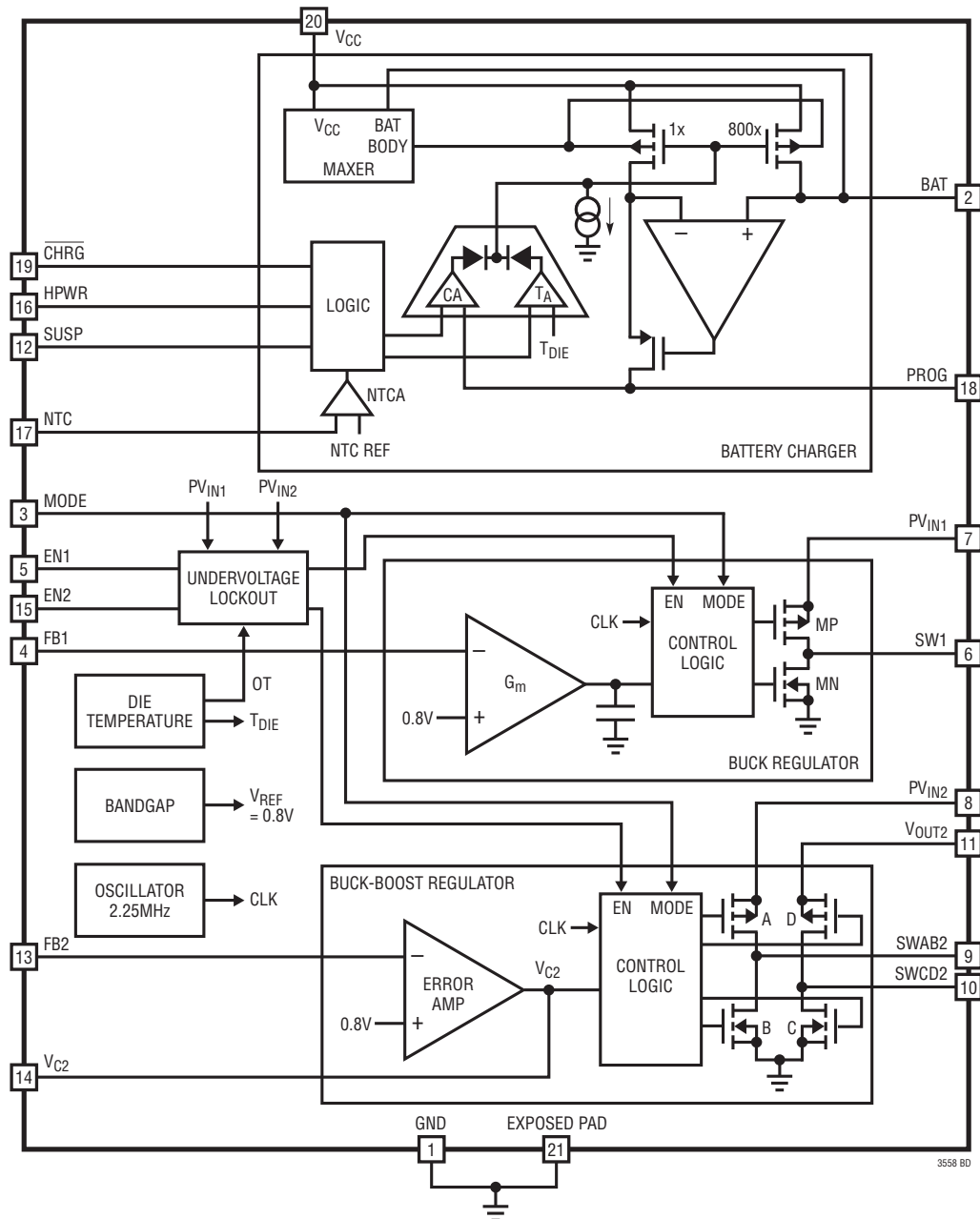
## PIN FUNCTIONS

of the full-scale charge current), unresponsive battery (i.e., the battery voltage remains below 2.9V after one half hour of charging) and battery temperature out of range. CHRG requires a pull-up resistor and/or LED to provide indication.

**V<sub>CC</sub> (Pin 20):** Battery Charger Input. A 1μF decoupling capacitor to GND is recommended.

**Exposed Pad (Pin 21):** Ground. The Exposed Pad must be soldered to PCB ground to provide electrical contact and rated thermal performance.

## BLOCK DIAGRAM

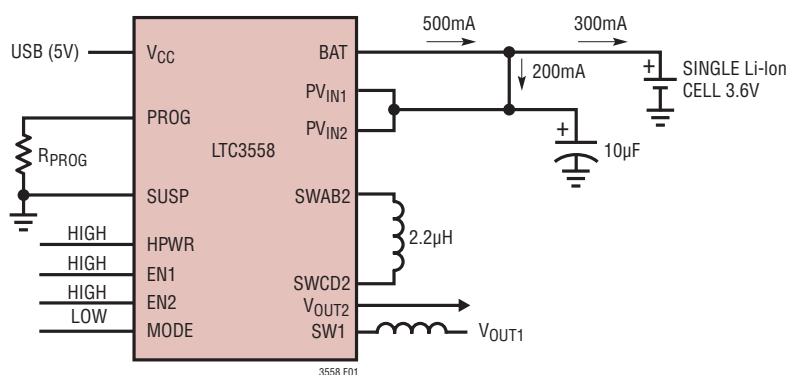


3558 BD



The battery charger employs a constant-current, constant-voltage charging algorithm and is capable of charging a single Li-Ion battery at charging currents up to 950mA. The user can program the maximum charging current available at the BAT pin via a single PROG resistor. The actual BAT pin current is set by the status of the HPWR pin.

For proper operation, the BAT, PV<sub>IN1</sub> and PV<sub>IN2</sub> pins must be tied together, as shown in Figure 1. Current being delivered at the BAT pin is 500mA. Both switching regulators are enabled. The sum of the average input currents drawn by both switching regulators is 200mA. This makes the effective battery charging current only 300mA. If the HPWR pin were tied LO, the BAT pin current would be 100mA. With the switching regulator conditions unchanged, this would cause the battery to discharge at 100mA.



**Figure 1. For Proper Operation, the BAT, PV<sub>IN1</sub> and PV<sub>IN2</sub> Pins Must Be Tied Together**

Furthermore, the battery charger is capable of operating from a USB power source. In this application, charge current can be programmed to a maximum of 100mA or 500mA per USB power specifications.

The undervoltage lockout circuit monitors the input voltage ( $V_{CC}$ ) and disables the battery charger until  $V_{CC}$  rises above  $V_{UVLO}$  (typically 4V). 200mV of hysteresis prevents oscillations around the trip point. In addition, a differential undervoltage lockout circuit disables the battery charger



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when  $V_{CC}$  falls to within  $V_{DUVLO}$  (typically 50mV) of the BAT voltage.

#### Suspend Mode

The battery charger can also be disabled by pulling the SUSP pin above 1.2V. In suspend mode, the battery drain current is reduced to 1.5 $\mu$ A and the input current is reduced to 8.5 $\mu$ A.

#### Charge Cycle Overview

When a battery charge cycle begins, the battery charger first determines if the battery is deeply discharged. If the battery voltage is below  $V_{TRKL}$ , typically 2.9V, an automatic trickle charge feature sets the battery charge current to 10% of the full-scale value.

Once the battery voltage is above 2.9V, the battery charger begins charging in constant-current mode. When the battery voltage approaches the 4.2V required to maintain a full charge, otherwise known as the float voltage, the charge current begins to decrease as the battery charger switches into constant-voltage mode.

#### Trickle Charge and Defective Battery Detection

Any time the battery voltage is below  $V_{TRKL}$ , the charger goes into trickle charge mode and reduces the charge current to 10% of the full-scale current. If the battery voltage remains below  $V_{TRKL}$  for more than 1/2 hour, the charger latches the bad-battery state, automatically terminates, and indicates via the  $\overline{CHRG}$  pin that the battery was unresponsive. If for any reason the battery voltage rises above  $V_{TRKL}$ , the charger will resume charging. Since the charger has latched the bad-battery state, if the battery voltage then falls below  $V_{TRKL}$  again but without rising past  $V_{RECHRG}$  first, the charger will immediately assume that the battery is defective. To reset the charger (i.e., when the dead battery is replaced with a new battery), simply remove the input voltage and reapply it or put the part in and out of suspend mode.

#### Charge Termination

The battery charger has a built-in safety timer that sets the total charge time for 4 hours. Once the battery voltage rises above  $V_{RECHRG}$  (typically 4.105V) and the charger

enters constant-voltage mode, the 4-hour timer is started. After the safety timer expires, charging of the battery will discontinue and no more current will be delivered.

#### Automatic Recharge

After the battery charger terminates, it will remain off, drawing only microamperes of current from the battery. If the portable product remains in this state long enough, the battery will eventually self discharge. To ensure that the battery is always topped off, a charge cycle will automatically begin when the battery voltage falls below  $V_{RECHRG}$  (typically 4.105V). In the event that the safety timer is running when the battery voltage falls below  $V_{RECHRG}$ , it will reset back to zero. To prevent brief excursions below  $V_{RECHRG}$  from resetting the safety timer, the battery voltage must be below  $V_{RECHRG}$  for more than 1.7ms. The charge cycle and safety timer will also restart if the  $V_{CC}$  UVLO or DUVLO cycles low and then high (e.g.,  $V_{CC}$  is removed and then replaced) or the charger enters and then exits suspend mode.

#### Programming Charge Current

The PROG pin serves both as a charge current program pin, and as a charge current monitor pin. By design, the PROG pin current is 1/800th of the battery charge current. Therefore, connecting a resistor from PROG to ground programs the charge current while measuring the PROG pin voltage allows the user to calculate the charge current.

Full-scale charge current is defined as 100% of the constant-current mode charge current programmed by the PROG resistor. In constant-current mode, the PROG pin serves to 1V if HPWR is high, which corresponds to charging at the full-scale charge current, or 200mV if HPWR is low, which corresponds to charging at 20% of the full-scale charge current. Thus, the full-scale charge current and desired program resistor for a given full-scale charge current are calculated using the following equations:

$$I_{CHG} = \frac{800V}{R_{PROG}}$$

$$R_{PROG} = \frac{800V}{I_{CHG}}$$

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In any mode, the actual battery current can be determined by monitoring the PROG pin voltage and using the following equation:

$$I_{BAT} = \frac{V_{PROG}}{R_{PROG}} \cdot 800$$

### Thermal Regulation

To prevent thermal damage to the IC or surrounding components, an internal thermal feedback loop will automatically decrease the programmed charge current if the die temperature rises to approximately 115°C. Thermal regulation protects the battery charger from excessive temperature due to high power operation or high ambient thermal conditions and allows the user to push the limits of the power handling capability with a given circuit board design without risk of damaging the LTC3558 or external components. The benefit of the LTC3558 battery charger thermal regulation loop is that charge current can be set according to actual conditions rather than worst-case conditions with the assurance that the battery charger will automatically reduce the current in worst-case conditions.

### Charge Status Indication

The  $\overline{CHRG}$  pin indicates the status of the battery charger. Four possible states are represented by  $\overline{CHRG}$  charging, not charging, unresponsive battery and battery temperature out of range.

The signal at the  $\overline{CHRG}$  pin can be easily recognized as one of the above four states by either a human or a microprocessor. The  $\overline{CHRG}$  pin, which is an open-drain output, can drive an indicator LED through a current limiting resistor for human interfacing, or simply a pull-up resistor for microprocessor interfacing.

To make the  $\overline{CHRG}$  pin easily recognized by both humans and microprocessors, the pin is either a low for charging, a high for not charging, or it is switched at high frequency (35kHz) to indicate the two possible faults: unresponsive battery and battery temperature out of range.

When charging begins,  $\overline{CHRG}$  is pulled low and remains low for the duration of a normal charge cycle. When the

charge current has dropped to below 10% of the full-scale current, the  $\overline{CHRG}$  pin is released (high impedance). If a fault occurs after the  $\overline{CHRG}$  pin is released, the pin remains high impedance. However, if a fault occurs before the  $\overline{CHRG}$  pin is released, the pin is switched at 35kHz. While switching, its duty cycle is modulated between a high and low value at a very low frequency. The low and high duty cycles are disparate enough to make an LED appear to be on or off thus giving the appearance of “blinking”. Each of the two faults has its own unique “blink” rate for human recognition as well as two unique duty cycles for microprocessor recognition.

Table 1 illustrates the four possible states of the  $\overline{CHRG}$  pin when the battery charger is active.

Table 1.  $\overline{CHRG}$  Output Pin

STATUS	FREQUENCY	MODULATION (BLINK) FREQUENCY	DUTY CYCLE
Charging	0Hz	0 Hz (Lo-Z)	100%
$I_{BAT} < C/10$	0Hz	0 Hz (Hi-Z)	0%
NTC Fault	35kHz	1.5Hz at 50%	6.25%, 93.75%
Bad Battery	35kHz	6.1Hz at 50%	12.5%, 87.5%

An NTC fault is represented by a 35kHz pulse train whose duty cycle alternates between 6.25% and 93.75% at a 1.5Hz rate. A human will easily recognize the 1.5Hz rate as a “slow” blinking which indicates the out of range battery temperature while a microprocessor will be able to decode either the 6.25% or 93.75% duty cycles as an NTC fault.

If a battery is found to be unresponsive to charging (i.e., its voltage remains below  $V_{TRKL}$  for over 1/2 hour), the  $\overline{CHRG}$  pin gives the battery fault indication. For this fault, a human would easily recognize the frantic 6.1Hz “fast” blinking of the LED while a microprocessor would be able to decode either the 12.5% or 87.5% duty cycles as a bad battery fault.

Although very improbable, it is possible that a duty cycle reading could be taken at the bright-dim transition (low duty cycle to high duty cycle). When this happens the duty cycle reading will be precisely 50%. If the duty cycle reading is 50%, system software should disqualify it and take a new duty cycle reading.

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### NTC Thermistor

The battery temperature is measured by placing a negative temperature coefficient (NTC) thermistor close to the battery pack. The NTC circuitry is shown in Figure 3.

To use this feature, connect the NTC thermistor,  $R_{NTC}$ , between the NTC pin and ground, and a bias resistor,  $R_{NOM}$ , from  $V_{CC}$  to NTC.  $R_{NOM}$  should be a 1% resistor with a value equal to the value of the chosen NTC thermistor at 25°C ( $R_{25}$ ). A 100k thermistor is recommended since thermistor current is not measured by the battery charger and its current will have to be considered for compliance with USB specifications.

The battery charger will pause charging when the resistance of the NTC thermistor drops to 0.54 times the

value of  $R_{25}$  or approximately 54k (for a Vishay “Curve 1” thermistor, this corresponds to approximately 40°C). If the battery charger is in constant-voltage mode, the safety timer will pause until the thermistor indicates a return to a valid temperature.

As the temperature drops, the resistance of the NTC thermistor rises. The battery charger is also designed to pause charging when the value of the NTC thermistor increases to 3.25 times the value of  $R_{25}$ . For a Vishay “Curve 1” thermistor, this resistance, 325k, corresponds to approximately 0°C. The hot and cold comparators each have approximately 3°C of hysteresis to prevent oscillation about the trip point. Grounding the NTC pin disables all NTC functionality.

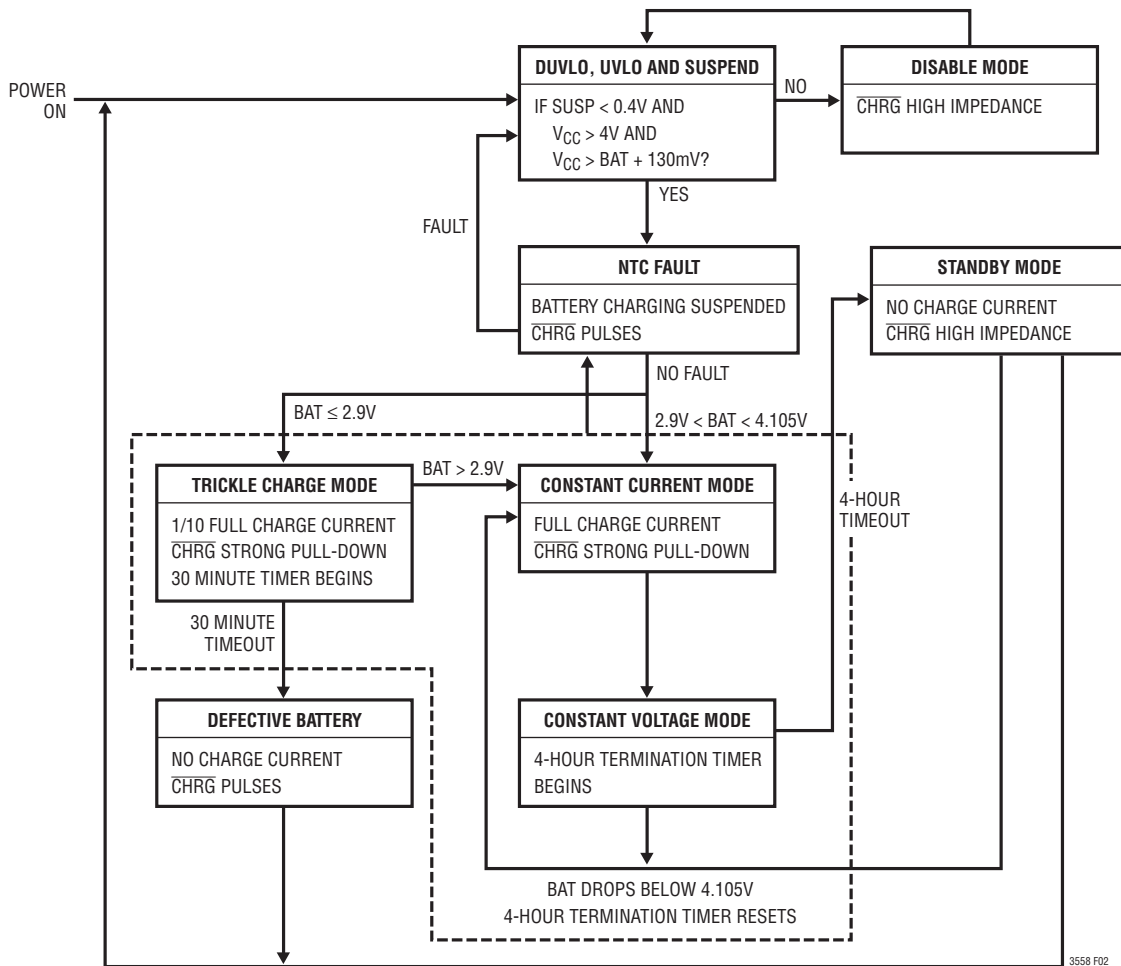


Figure 2. State Diagram of Battery Charger Operation

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### Alternate NTC Thermistors and Biasing

The battery charger provides temperature qualified charging if a grounded thermistor and a bias resistor are connected to the NTC pin. By using a bias resistor whose value is equal to the room temperature resistance of the thermistor (R25) the upper and lower temperatures are pre-programmed to approximately 40°C and 0°C, respectively (assuming a Vishay “Curve 1” thermistor).

The upper and lower temperature thresholds can be adjusted by either a modification of the bias resistor value or by adding a second adjustment resistor to the circuit. If only the bias resistor is adjusted, then either the upper or the lower threshold can be modified but not both. The other trip point will be determined by the characteristics of the thermistor. Using the bias resistor in addition to an adjustment resistor, both the upper and the lower temperature trip points can be independently programmed with the constraint that the difference between the upper and lower temperature thresholds cannot decrease. Examples of each technique are given below.

NTC thermistors have temperature characteristics which are indicated on resistance-temperature conversion tables. The Vishay-Dale thermistor NTHS0603N011-N1003F, used in the following examples, has a nominal value of 100k and follows the Vishay “Curve 1” resistance-temperature characteristic.

In the explanation below, the following notation is used.

R25 = Value of the thermistor at 25°C

R<sub>NTC|COLD</sub> = Value of thermistor at the cold trip point

R<sub>NTC|HOT</sub> = Value of the thermistor at the hot trip point

r<sub>COLD</sub> = Ratio of R<sub>NTC|COLD</sub> to R25

r<sub>HOT</sub> = Ratio of R<sub>NTC|HOT</sub> to R25

R<sub>NOM</sub> = Primary thermistor bias resistor (see Figure 3)

R1 = Optional temperature range adjustment resistor (see Figure 4)

The trip points for the battery charger’s temperature qualification are internally programmed at 0.349 • V<sub>CC</sub> for the hot threshold and 0.765 • V<sub>CC</sub> for the cold threshold.

Therefore, the hot trip point is set when:

$$\frac{R_{NTC|HOT}}{R_{NOM} + R_{NTC|HOT}} \cdot V_{CC} = 0.349 \cdot V_{CC}$$

and the cold trip point is set when:

$$\frac{R_{NTC|COLD}}{R_{NOM} + R_{NTC|COLD}} \cdot V_{CC} = 0.765 \cdot V_{CC}$$

Solving these equations for R<sub>NTC|COLD</sub> and R<sub>NTC|HOT</sub> results in the following:

$$R_{NTC|HOT} = 0.536 \cdot R_{NOM}$$

and

$$R_{NTC|COLD} = 3.25 \cdot R_{NOM}$$

By setting R<sub>NOM</sub> equal to R25, the above equations result in r<sub>HOT</sub> = 0.536 and r<sub>COLD</sub> = 3.25. Referencing these ratios to the Vishay Resistance-Temperature Curve 1 chart gives a hot trip point of about 40°C and a cold trip point of about 0°C. The difference between the hot and cold trip points is approximately 40°C.

By using a bias resistor, R<sub>NOM</sub>, different in value from R25, the hot and cold trip points can be moved in either direction. The temperature span will change somewhat due to the nonlinear behavior of the thermistor. The following equations can be used to easily calculate a new value for the bias resistor:

$$R_{NOM} = \frac{r_{HOT}}{0.536} \cdot R25$$

$$R_{NOM} = \frac{r_{COLD}}{3.25} \cdot R25$$

where r<sub>HOT</sub> and r<sub>COLD</sub> are the resistance ratios at the desired hot and cold trip points. Note that these equations are linked. Therefore, only one of the two trip points can be chosen, the other is determined by the default ratios designed in the IC. Consider an example where a 60°C hot trip point is desired.

From the Vishay Curve 1 R-T characteristics, r<sub>HOT</sub> is 0.2488 at 60°C. Using the above equation, R<sub>NOM</sub> should be set

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to 46.4k. With this value of  $R_{NOM}$ , the cold trip point is about 16°C. Notice that the span is now 44°C rather than the previous 40°C.

The upper and lower temperature trip points can be independently programmed by using an additional bias resistor as shown in Figure 4. The following formulas can be used to compute the values of  $R_{NOM}$  and  $R1$ :

$$R_{NOM} = \frac{r_{COLD} - r_{HOT}}{2.714} \cdot R25$$

$$R1 = 0.536 \cdot R_{NOM} - r_{HOT} \cdot R25$$

For example, to set the trip points to 0°C and 45°C with a Vishay Curve 1 thermistor choose:

$$R_{NOM} = \frac{3.266 - 0.4368}{2.714} \cdot 100k = 104.2k$$

the nearest 1% value is 105k.

$$R1 = 0.536 \cdot 105k - 0.4368 \cdot 100k = 12.6k$$

the nearest 1% value is 12.7k. The final solution is shown in Figure 4 and results in an upper trip point of 45°C and a lower trip point of 0°C.

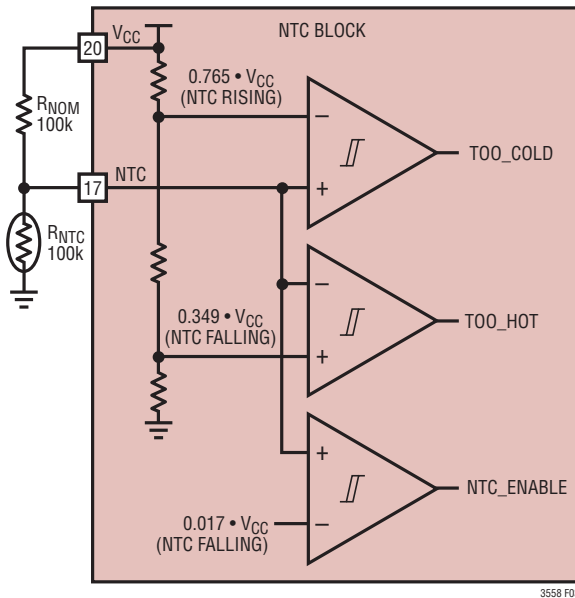


Figure 3. Typical NTC Thermistor Circuit

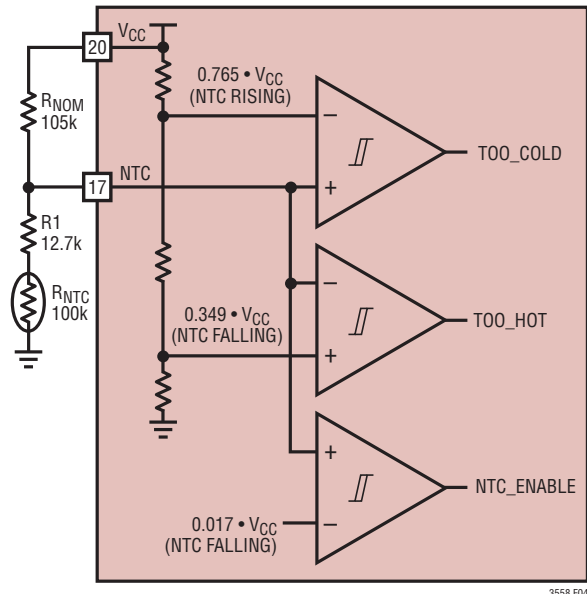


Figure 4. NTC Thermistor Circuit with Additional Bias Resistor



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### USB and Wall Adapter Power

Although the battery charger is designed to draw power from a USB port to charge Li-Ion batteries, a wall adapter can also be used. Figure 5 shows an example of how to combine wall adapter and USB power inputs. A P-channel MOSFET, MP1, is used to prevent back conduction into the USB port when a wall adapter is present and Schottky diode, D1, is used to prevent USB power loss through the 1k pull-down resistor.

Typically, a wall adapter can supply significantly more current than the 500mA-limited USB port. Therefore, an N-channel MOSFET, MN1, and an extra program resistor are used to increase the maximum charge current to 950mA when the wall adapter is present.

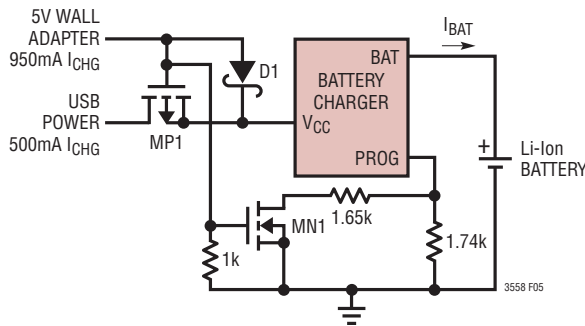


Figure 5. Combining Wall Adapter and USB Power

### Power Dissipation

The conditions that cause the LTC3558 to reduce charge current through thermal feedback can be approximated by considering the power dissipated in the IC. For high charge currents, the LTC3558 power dissipation is approximately:

$$P_D = (V_{CC} - V_{BAT}) \cdot I_{BAT}$$

where  $P_D$  is the power dissipated,  $V_{CC}$  is the input supply voltage,  $V_{BAT}$  is the battery voltage, and  $I_{BAT}$  is the charge

current. It is not necessary to perform any worst-case power dissipation scenarios because the LTC3558 will automatically reduce the charge current to maintain the die temperature at approximately 105°C. However, the approximate ambient temperature at which the thermal feedback begins to protect the IC is:

$$T_A = 105^\circ\text{C} - P_D \theta_{JA}$$

$$T_A = 105^\circ\text{C} - (V_{CC} - V_{BAT}) \cdot I_{BAT} \cdot \theta_{JA}$$

Example: Consider an LTC3558 operating from a USB port providing 500mA to a 3.5V Li-Ion battery. The ambient temperature above which the LTC3558 will begin to reduce the 500mA charge current is approximately:

$$T_A = 105^\circ\text{C} - (5\text{V} - 3.5\text{V}) \cdot (500\text{mA}) \cdot 68^\circ\text{C/W}$$

$$T_A = 105^\circ\text{C} - 0.75\text{W} \cdot 68^\circ\text{C/W} = 105^\circ\text{C} - 51^\circ\text{C}$$

$$T_A = 54^\circ\text{C}$$

The LTC3558 can be used above 70°C, but the charge current will be reduced from 500mA. The approximate current at a given ambient temperature can be calculated:

$$I_{BAT} = \frac{105^\circ\text{C} - T_A}{(V_{CC} - V_{BAT}) \cdot \theta_{JA}}$$

Using the previous example with an ambient temperature of 88°C, the charge current will be reduced to approximately:

$$I_{BAT} = \frac{105^\circ\text{C} - 88^\circ\text{C}}{(5\text{V} - 3.5\text{V}) \cdot 68^\circ\text{C/W}} = \frac{17^\circ\text{C}}{102^\circ\text{C/A}}$$

$$I_{BAT} = 167\text{mA}$$

Furthermore, the voltage at the PROG pin will change proportionally with the charge current as discussed in the Programming Charge Current section.

It is important to remember that LTC3558 applications do not need to be designed for worst-case thermal conditions since the IC will automatically reduce power dissipation when the junction temperature reaches approximately 105°C.

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#### Battery Charger Stability Considerations

The LTC3558 battery charger contains two control loops: the constant-voltage and constant-current loops. The constant-voltage loop is stable without any compensation when a battery is connected with low impedance leads. Excessive lead length, however, may add enough series inductance to require a bypass capacitor of at least 1.5μF from BAT to GND. Furthermore, a 4.7μF capacitor with a 0.2Ω to 1Ω series resistor from BAT to GND is required to keep ripple voltage low when the battery is disconnected.

High value capacitors with very low ESR (especially ceramic) reduce the constant-voltage loop phase margin, possibly resulting in instability. Ceramic capacitors up to 22μF may be used in parallel with a battery, but larger ceramics should be decoupled with 0.2Ω to 1Ω of series resistance.

In constant-current mode, the PROG pin is in the feedback loop, not the battery. Because of the additional pole created by the PROG pin capacitance, capacitance on this pin must be kept to a minimum. With no additional capacitance on the PROG pin, the charger is stable with program resistor values as high as 25K. However, additional capacitance on this node reduces the maximum allowed program resistor. The pole frequency at the PROG pin should be kept above 100kHz. Therefore, if the PROG pin is loaded with a capacitance,  $C_{PROG}$ , the following equation should be used to calculate the maximum resistance value for  $R_{PROG}$ :

$$R_{PROG} \leq \frac{1}{2\pi \cdot 10^5 \cdot C_{PROG}}$$

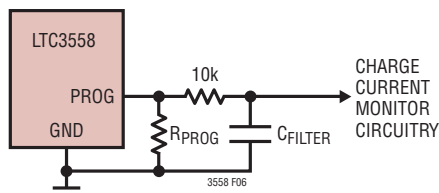


Figure 6. Isolated Capacitive Load on PROG Pin and Filtering

Average, rather than instantaneous, battery current may be of interest to the user. For example, if a switching power supply operating in low-current mode is connected in parallel with the battery, the average current being pulled out of the BAT pin is typically of more interest than the instantaneous current pulses. In such a case, a simple RC filter can be used on the PROG pin to measure the average battery current as shown in Figure 6. A 10k resistor has been added between the PROG pin and the filter capacitor to ensure stability.

#### USB Inrush Limiting

When a USB cable is plugged into a portable product, the inductance of the cable and the high-Q ceramic input capacitor form an L-C resonant circuit. If there is not much impedance in the cable, it is possible for the voltage at the input of the product to reach as high as twice the USB voltage (~10V) before it settles out. In fact, due to the high voltage coefficient of many ceramic capacitors (a nonlinearity), the voltage may even exceed twice the USB voltage. To prevent excessive voltage from damaging the LTC3558 during a hot insertion, the soft connect circuit in Figure 7 can be employed.

In the circuit of Figure 7, capacitor C1 holds MP1 off when the cable is first connected. Eventually C1 begins to charge up to the USB input voltage applying increasing gate support to MP1. The long time constant of R1 and C1 prevents the current from building up in the cable too fast thus dampening out any resonant overshoot.

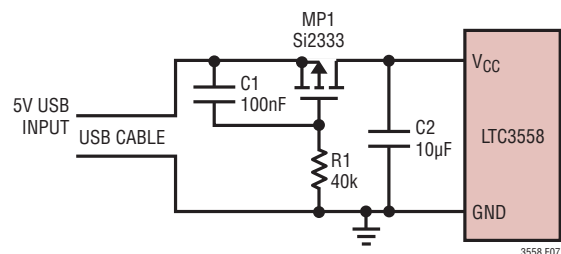


Figure 7. USB Soft Connect Circuit

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### Buck Switching Regulator General Information

The LTC3558 contains a 2.25MHz constant-frequency current mode buck switching regulator that can provide up to 400mA. The switcher can be programmed for a minimum output voltage of 0.8V and can be used to power a microcontroller core, microcontroller I/O, memory or other logic circuitry. The regulator supports 100% duty cycle operation (dropout mode) when the input voltage drops very close to the output voltage and is also capable of operating in Burst Mode operation for highest efficiencies at light loads (Burst Mode operation is pin selectable). The buck switching regulator also includes soft-start to limit inrush current when powering on, short-circuit current protection, and switch node slew limiting circuitry to reduce radiated EMI.

A MODE pin sets the buck switching regulator in Burst Mode operation or pulse skip operating mode. The regulator is enabled individually through its enable pin. The buck regulator input supply (PV<sub>IN1</sub>) should be connected to the battery pin (BAT) and PV<sub>IN2</sub>. This allows the undervoltage lockout circuit on the BAT pin to disable the buck regulators when the BAT voltage drops below 2.45V. Do not drive the buck switching regulator from a voltage other than BAT. A 10µF decoupling capacitor from the PV<sub>IN1</sub> pin to GND is recommended.

### Buck Switching Regulator Output Voltage Programming

The buck switching regulator can be programmed for output voltages greater than 0.8V. The output voltage for the buck switching regulator is programmed using a resistor divider from the switching regulator output connected to its feedback pin (FB1), as shown in Figure 8, such that:

$$V_{OUT} = 0.8(1 + R1/R2)$$

Typical values for R1 are in the range of 40k to 1M. The capacitor C<sub>FB</sub> cancels the pole created by feedback resistors and the input capacitance of the FB pin and also helps to improve transient response for output voltages much greater than 0.8V. A variety of capacitor sizes can be used for C<sub>FB</sub> but a value of 10pF is recommended for most applications. Experimentation with capacitor sizes between 2pF and 22pF may yield improved transient response if so desired by the user.

### Buck Switching Regulator Operating Modes

The buck switching regulator includes two possible operating modes to meet the noise/power needs of a variety of applications.

In pulse skip mode, an internal latch is set at the start of every cycle, which turns on the main P-channel MOSFET

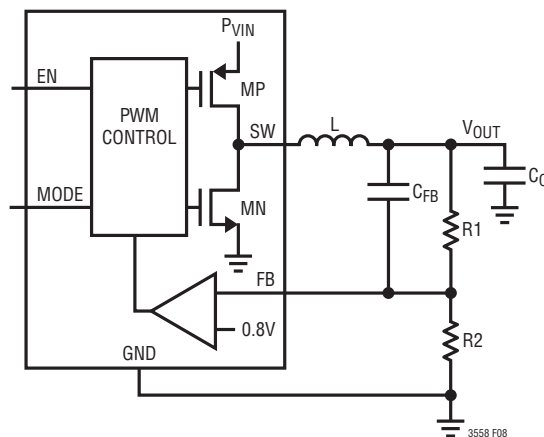


Figure 8. Buck Converter Application Circuit



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switch. During each cycle, a current comparator compares the peak inductor current to the output of an error amplifier. The output of the current comparator resets the internal latch, which causes the main P-channel MOSFET switch to turn off and the N-channel MOSFET synchronous rectifier to turn on. The N-channel MOSFET synchronous rectifier turns off at the end of the 2.25MHz cycle or if the current through the N-channel MOSFET synchronous rectifier drops to zero. Using this method of operation, the error amplifier adjusts the peak inductor current to deliver the required output power. All necessary compensation is internal to the buck switching regulator requiring only a single ceramic output capacitor for stability. At light loads in pulse skip mode, the inductor current may reach zero on each pulse which will turn off the N-channel MOSFET synchronous rectifier. In this case, the switch node (SW1) goes high impedance and the switch node voltage will “ring”. This is discontinuous operation, and is normal behavior for a switching regulator. At very light loads in pulse skip mode, the buck switching regulator will automatically skip pulses as needed to maintain output regulation. At high duty cycle ( $V_{OUT} > PV_{IN1}/2$ ) in pulse skip mode, it is possible for the inductor current to reverse causing the buck converter to switch continuously. Regulation and low noise operation are maintained but the input supply current will increase to a couple mA due to the continuous gate switching.

During Burst Mode operation, the buck switching regulator automatically switches between fixed frequency PWM operation and hysteretic control as a function of the load current. At light loads the buck switching regulator controls the inductor current directly and use a hysteretic control loop to minimize both noise and switching losses. During Burst Mode operation, the output capacitor is charged to a voltage slightly higher than the regulation point. The buck switching regulator then goes into sleep mode, during which the output capacitor provides the load current. In sleep mode, most of the switching regulator’s circuitry is

powered down, helping conserve battery power. When the output voltage drops below a pre-determined value, the buck switching regulator circuitry is powered on and another burst cycle begins. The sleep time decreases as the load current increases. Beyond a certain load current point (about 1/4 rated output load current) the buck switching regulator will switch to a low noise constant-frequency PWM mode of operation, much the same as pulse skip operation at high loads. For applications that can tolerate some output ripple at low output currents, Burst Mode operation provides better efficiency than pulse skip at light loads.

The buck switching regulator allows mode transition on-the-fly, providing seamless transition between modes even under load. This allows the user to switch back and forth between modes to reduce output ripple or increase low current efficiency as needed. Burst Mode operation is set by driving the MODE pin high, while pulse skip mode is achieved by driving the MODE pin low.

**Buck Switching Regulator in Shutdown**

The buck switching regulator is in shutdown when not enabled for operation. In shutdown, all circuitry in the buck switching regulator is disconnected from the regulator input supply, leaving only a few nanoamps of leakage pulled to ground through a 13k resistor on the switch (SW1) pin when in shutdown.

**Buck Switching Regulator Dropout Operation**

It is possible for the buck switching regulator’s input voltage to approach its programmed output voltage (e.g., a battery voltage of 3.4V with a programmed output voltage of 3.3V). When this happens, the PMOS switch duty cycle increases until it is turned on continuously at 100%. In this dropout condition, the respective output voltage equals the regulator’s input voltage minus the voltage drops across the internal P-channel MOSFET and the inductor.

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### Buck Switching Regulator Soft-Start Operation

Soft-start is accomplished by gradually increasing the peak inductor current for each switching regulator over a 500 $\mu$ s period. This allows an output to rise slowly, helping minimize the battery in-rush current required to charge up the regulator's output capacitor. A soft-start cycle occurs when the buck switcher first turns on, or after a fault condition has occurred (thermal shutdown or UVLO). A soft-start cycle is not triggered by changing operating modes using the MODE pin. This allows seamless output operation when transitioning between operating modes.

### Buck Switching Regulator Switching Slew Rate Control

The buck switching regulator contains circuitry to limit the slew rate of the switch node (SW1). This circuitry is designed to transition the switch node over a period of a couple of nanoseconds, significantly reducing radiated EMI and conducted supply noise while maintaining high efficiency.

### Buck Switching Regulator Low Supply Operation

An undervoltage lockout (UVLO) circuit on  $PV_{IN1}$  shuts down the step-down switching regulators when BAT drops below 2.45V. This UVLO prevents the buck switching regulator from operating at low supply voltages where loss of regulation or other undesirable operation may occur.

### Buck Switching Regulator Inductor Selection

The buck switching regulator is designed to work with inductors in the range of 2.2 $\mu$ H to 10 $\mu$ H, but for most applications a 4.7 $\mu$ H inductor is suggested. Larger value inductors reduce ripple current which improves output ripple voltage. Lower value inductors result in higher ripple current which improves transient response time. To maximize efficiency, choose an inductor with a low DC resistance. For a 1.2V output efficiency is reduced about 2% for every 100m $\Omega$  series resistance at 400mA load current, and about 2% for every 300m $\Omega$  series resistance at 100mA load current. Choose an inductor with a DC current rating at least 1.5 times larger than the maximum load current to ensure that the inductor does not saturate during normal operation. If output short-circuit is a possible condition the inductor should be rated to handle the maximum peak current specified for the buck regulators.

Different core materials and shapes will change the size/current and price/current relationship of an inductor. Toroid or shielded pot cores in ferrite or permalloy materials are small and don't radiate much energy, but generally cost more than powdered iron core inductors with similar electrical characteristics. Inductors that are very thin or have a very small volume typically have much higher DCR losses, and will not give the best efficiency. The choice of which style inductor to use often depends more on the price vs size, performance, and any radiated EMI requirements than on what the buck regulator requires to operate.

The inductor value also has an effect on Burst Mode operation. Lower inductor values will cause Burst Mode switching frequency to increase.

# LTC3558

## APPLICATIONS INFORMATION

Table 2 shows several inductors that work well with the LTC3558 buck switching regulator. These inductors offer a good compromise in current rating, DCR and physical size. Consult each manufacturer for detailed information on their entire selection of inductors.

### Buck Switching Regulator Input/Output Capacitor Selection

Low ESR (equivalent series resistance) ceramic capacitors should be used at switching regulator outputs as well as the switching regulator input supply. Ceramic capacitor dielectrics are a compromise between high dielectric constant and stability versus temperature and versus DC bias voltage. The X5R/X7R dielectrics offer the best compromise with high dielectric constant and acceptable performance over temperature and under bias. Do not use Y5V dielectrics. A 10 $\mu$ F output capacitor is sufficient

for most applications. For good transient response and stability the output capacitor should retain at least 4 $\mu$ F of capacitance over operating temperature and bias voltage. The buck switching regulator input supply should be bypassed with a 10 $\mu$ F capacitor. Consult manufacturer for detailed information on their selection and specifications of ceramic capacitors. Many manufacturers now offer very thin (< 1mm tall) ceramic capacitors ideal for use in height-restricted designs. Table 3 shows a list of several ceramic capacitor manufacturers.

**Table 3: Recommended Ceramic Capacitor Manufacturers**

AVX	(803) 448-9411	<a href="http://www.avxcorp.com">www.avxcorp.com</a>
Murata	(714) 852-2001	<a href="http://www.murata.com">www.murata.com</a>
Taiyo Yuden	(408) 537-4150	<a href="http://www.t-yuden.com">www.t-yuden.com</a>
TDK	(888) 835-6646	<a href="http://www.tdk.com">www.tdk.com</a>

**Table 2. Recommended Inductors for Buck Switching Regulators**

INDUCTOR TYPE	L ( $\mu$ H)	MAX I <sub>DC</sub> (A)	MAX DCR (m $\Omega$ )	SIZE IN mm (L $\times$ W $\times$ H)	MANUFACTURER
DE2818C	4.7	1.25	72*	3 $\times$ 2.8 $\times$ 1.8	Toko
DE2812C	4.7	1.15	130*	3 $\times$ 2.8 $\times$ 1.2	<a href="http://www.toko.com">www.toko.com</a>
CDRH3D16	4.7	0.9	110	4 $\times$ 4 $\times$ 1.8	Sumida <a href="http://www.sumida.com">www.sumida.com</a>
SD3118	4.7	1.3	162	3.1 $\times$ 3.1 $\times$ 1.8	Cooper
SD3112	4.7	0.8	246	3.1 $\times$ 3.1 $\times$ 1.2	<a href="http://www.cooperet.com">www.cooperet.com</a>
LPS3015	4.7	1.1	200	3 $\times$ 3 $\times$ 1.5	Coilcraft <a href="http://www.coilcraft.com">www.coilcraft.com</a>

\*Typical DCR

## APPLICATIONS INFORMATION

### Buck-Boost Switching Regulator

The LTC3558 contains a 2.25MHz constant-frequency, voltage mode, buck-boost switching regulator. The regulator provides up to 400mA of output load current. The buck-boost switching regulator can be programmed for a minimum output voltage of 2.75V and can be used to power a microcontroller core, microcontroller I/O, memory, disk drive, or other logic circuitry. To suit a variety of applications, different mode functions allow the user to trade off noise for efficiency. Two modes are available to control the operation of the buck-boost regulator. At moderate to heavy loads, the constant-frequency PWM mode provides the least noise switching solution. At lighter loads, Burst Mode operation may be selected. Regulation is maintained by an error amplifier that compares the divided output voltage with a reference and adjusts the compensation voltage accordingly until the FB2 voltage has stabilized at 0.8V. The buck-boost switching regulator also includes soft-start to limit inrush current and voltage overshoot when powering on, short-circuit current protection, and switch node slew limiting circuitry for reduced radiated EMI.

### Buck-Boost Regulator PWM Operating Mode

In PWM mode, the voltage seen at the feedback node is compared to a 0.8V reference. From the feedback voltage, an error amplifier generates an error signal seen at the  $V_{C2}$  pin. This error signal controls PWM waveforms that modulate switches A (input PMOS), B (input NMOS), C (output NMOS), and D (output PMOS). Switches A and B operate synchronously, as do switches C and D. If the input voltage is significantly greater than the programmed output voltage, then the regulator will operate in buck mode. In this case, switches A and B will be modulated, with switch D always on (and switch C always off), to step-down the input voltage to the programmed output. If the input voltage is significantly less than the programmed output voltage, then the converter will operate in boost mode. In this case, switches C and D are modulated, with switch A always on (and switch B always off), to step up the input voltage to the programmed output. If the input voltage is close to the programmed output voltage, then

the converter will operate in four-switch mode. While operating in four-switch mode, switches turn on as per the following sequence: switches A and D → switches A and C → switches B and D → switches A and D.

### Buck-Boost Regulator Burst Mode Operation

In Burst Mode operation, the switching regulator uses a hysteretic feedback voltage algorithm to control the output voltage. By limiting FET switching and using a hysteretic control loop switching losses are greatly reduced. In this mode, output current is limited to 50mA. While in Burst Mode operation, the output capacitor is charged to a voltage slightly higher than the regulation point. The buck-boost converter then goes into a SLEEP state, during which the output capacitor provides the load current. The output capacitor is charged by charging the inductor until the input current reaches 250mA typical, and then discharging the inductor until the reverse current reaches 0mA typical. This process of bursting current is repeated until the feedback voltage has charged to the reference voltage plus 6mV (806mV typical). In the SLEEP state, most of the regulator's circuitry is powered down, helping to conserve battery power. When the feedback voltage drops below the reference voltage minus 6mV (794mV typical), the switching regulator circuitry is powered on and another burst cycle begins. The duration for which the regulator operates in SLEEP depends on the load current and output capacitor value. The SLEEP time decreases as the load current increases. The maximum deliverable load current in Burst Mode operation is 50mA typical. The buck-boost regulator may not enter SLEEP if the load current is greater than 50mA. If the load current increases beyond this point while in Burst Mode operation, the output may lose regulation. Burst Mode operation provides a significant improvement in efficiency at light loads at the expense of higher output ripple when compared to PWM mode. For many noise-sensitive systems, Burst Mode operation might be undesirable at certain times (i.e., during a transmit or receive cycle of a wireless device), but highly desirable at others (i.e., when the device is in low power standby mode).

## LTC3558

### APPLICATIONS INFORMATION

#### Buck-Boost Switching Regulator Output Voltage Programming

The buck-boost switching regulator can be programmed for output voltages greater than 2.75V and less than 5.45V. To program the output voltage, a resistor divider is connected between  $V_{OUT2}$  and the feedback node (FB2) as shown in Figure 9. The output voltage is given by  $V_{OUT2} = 0.8(1 + R1/R2)$ .

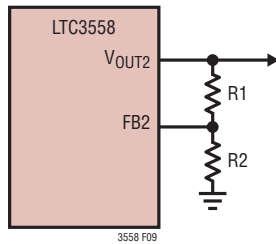


Figure 9. Programming the Buck-Boost Output Voltage Requires a Resistor Divider Connected Between  $V_{OUT2}$  and FB2

#### Closing the Feedback Loop

The LTC3558 incorporates voltage mode PWM control. The control to output gain varies with operation region (buck, boost, buck-boost), but is usually no greater than 20. The output filter exhibits a double pole response given by:

$$f_{\text{FILTER\_POLE}} = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C_{\text{OUT}}}} \text{ Hz}$$

where  $C_{\text{OUT}}$  is the output filter capacitor.

The output filter zero is given by:

$$f_{\text{FILTER\_ZERO}} = \frac{1}{2 \cdot \pi \cdot R_{\text{ESR}} \cdot C_{\text{OUT}}} \text{ Hz}$$

where  $R_{\text{ESR}}$  is the capacitor equivalent series resistance.

A troublesome feature in boost mode is the right-half plane zero (RHP), and is given by:

$$f_{\text{RHPZ}} = \frac{PV_{\text{IN2}}^2}{2 \cdot \pi \cdot I_{\text{OUT}} \cdot L \cdot V_{\text{OUT2}}} \text{ Hz}$$

The loop gain is typically rolled off before the RHP zero frequency.

A simple Type I compensation network, as shown in Figure 10, can be incorporated to stabilize the loop, but at the cost of reduced bandwidth and slower transient response. To ensure proper phase margin, the loop requires to be crossed over a decade before the LC double pole.

The unity-gain frequency of the error amplifier with the Type I compensation is given by:

$$f_{\text{UG}} = \frac{1}{2 \cdot \pi \cdot R1 \cdot C_{\text{P1}}} \text{ Hz}$$

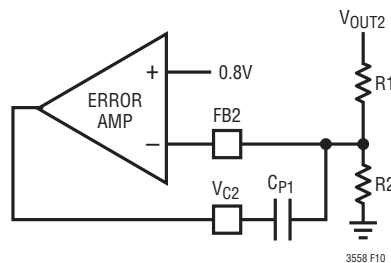


Figure 10. Error Amplifier with Type I Compensation



## APPLICATIONS INFORMATION

Most applications demand an improved transient response to allow a smaller output filter capacitor. To achieve a higher bandwidth, Type III compensation is required. Two zeros are required to compensate for the double-pole response. Type III compensation also reduces any  $V_{OUT2}$  overshoot seen during a start-up condition. A Type III compensation circuit is shown in Figure 11 and yields the following transfer function:

$$\frac{V_{C2}}{V_{OUT2}} = \frac{1}{R1(C1 + C2)}$$

$$\bullet \frac{(1 + sR2C2)[1 + s(R1 + R3)C3]}{s[1 + sR2(C1 || C2)](1 + sR3C3)}$$

A Type III compensation network attempts to introduce a phase bump at a higher frequency than the LC double pole. This allows the system to cross unity gain after the LC double pole, and achieve a higher bandwidth. While attempting to cross over after the LC double pole, the system must still cross over before the boost right-half plane zero. If unity gain is not reached sufficiently before the right-half plane zero, then the  $-180^\circ$  of phase lag from the LC double pole combined with the  $-90^\circ$  of phase lag from the right-half plane zero will result in negating the phase bump of the compensator.

The compensator zeros should be placed either before or only slightly after the LC double pole such that their positive phase contributions offset the  $-180^\circ$  that occurs

at the filter double pole. If they are placed at too low of a frequency, they will introduce too much gain to the system and the crossover frequency will be too high. The two high frequency poles should be placed such that the system crosses unity gain during the phase bump introduced by the zeros and before the boost right-half plane zero and such that the compensator bandwidth is less than the bandwidth of the error amp (typically 900kHz). If the gain of the compensation network is ever greater than the gain of the error amplifier, then the error amplifier no longer acts as an ideal op amp, and another pole will be introduced at the same point.

Recommended Type III compensation components for a 3.3V output are:

R1: 324k $\Omega$

R<sub>FB</sub>: 105k $\Omega$

C1: 10pF

R2: 15k $\Omega$

C2: 330pF

R3: 121k $\Omega$

C3: 33pF

C<sub>OUT</sub>: 22 $\mu$ F

L<sub>OUT</sub>: 2.2 $\mu$ H

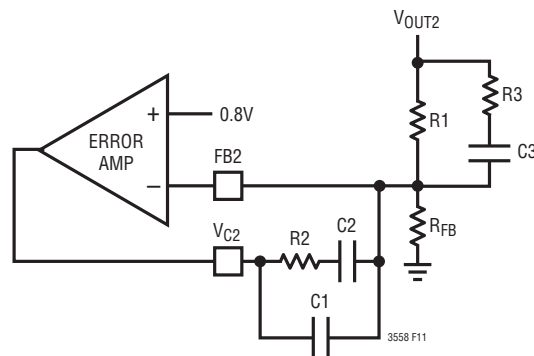


Figure 11. Error Amplifier with Type III Compensation

## LTC3558

### APPLICATIONS INFORMATION

#### Input Current Limit

The input current limit comparator will shut the input PMOS switch off once current exceeds 700mA typical. Before the switch current limit, the average current limit amp (620mA typical) will source current into the feedback pin to drop the output voltage. The input current limit also protects against a short-circuit condition at the  $V_{OUT2}$  pin.

#### Reverse Current Limit

The reverse current limit comparator will shut the output PMOS switch off once current returning from the output exceeds 450mA typical.

#### Output Overvoltage Protection

If the feedback node were inadvertently shorted to ground, then the output would increase indefinitely with the maximum current that could be sourced from the input supply. The buck-boost regulator protects against this by shutting off the input PMOS if the output voltage exceeds a 5.75V maximum.

#### Buck-Boost Regulator Soft-Start Operation

Soft-start is accomplished by gradually increasing the reference voltage over a 500 $\mu$ s typical period. A soft-start cycle occurs whenever the buck-boost is enabled, or after a fault condition has occurred (thermal shutdown or UVLO). A soft-start cycle is not triggered by changing operating modes. This allows seamless output operation when transitioning between Burst Mode operation and PWM mode operation.

#### Buck-Boost Switching Regulator Inductor Selection

The buck-boost switching regulator is designed to work with inductors in the range of 1 $\mu$ H to 5 $\mu$ H. For most applications, a 2.2 $\mu$ H inductor will suffice. Larger value inductors reduce ripple current which improves output ripple voltage. Lower value inductors result in higher ripple current and improved transient response time. To maximize efficiency, choose an inductor with a low DC resistance and a DC current rating at least 1.5 times larger than the maximum load current to ensure that the inductor does not saturate during normal operation. If output short-circuit is a possible condition, the inductor current should be rated to handle up to the peak current specified for the buck-boost regulator.

The inductor value also affects Burst Mode operation. Lower inductor values will cause Burst Mode switching frequencies to increase.

Different core materials and shapes will change the size/current and price/current relationship of an inductor. Toroid or shielded pot cores in ferrite or permalloy materials are small and do not radiate much energy, but cost more than powdered iron core inductors with similar electrical characteristics. Inductors that are very thin or have a very small volume typically have much higher core and DCR losses and will not give the best efficiency.

Table 4 shows some inductors that work well with the buck-boost regulator. These inductors offer a good compromise in current rating, DCR and physical size. Consult each manufacturer for detailed information on their entire selection of inductors.

**Table 4. Recommended Inductors for the Buck-Boost Switching Regulator.**

INDUCTOR TYPE	L ( $\mu$ H)	MAX $I_{DC}$ (A)	MAX DCR (m $\Omega$ )	SIZE IN mm (L $\times$ W $\times$ H)	MANUFACTURER
DB3018C	2.4	1.31	80	3.8 $\times$ 3.8 $\times$ 1.4	Toko <a href="http://www.toko.com">www.toko.com</a>
D312C	2.2	1.14	140	3.6 $\times$ 3.6 $\times$ 1.2	
DE2812C	2	1.4	81	3 $\times$ 3.2 $\times$ 1.2	
DE2812C	2.7	1.2	87	3 $\times$ 3.2 $\times$ 1.2	
CDRH3D16	2.2	1.2	72	4 $\times$ 4 $\times$ 1.8	Sumida <a href="http://www.sumida.com">www.sumida.com</a>
SD12	2.2	1.8	74	5.2 $\times$ 5.2 $\times$ 1.2	Cooper <a href="http://www.cooperet.com">www.cooperet.com</a>

\*Typical DCR

## APPLICATIONS INFORMATION

### Buck-Boost Switching Regulator Input/Output Capacitor Selection

Low ESR (equivalent series resistance) ceramic capacitors should be used at both the buck-boost regulator input ( $PV_{IN2}$ ) and the output ( $V_{OUT2}$ ). It is recommended that the input be bypassed with a  $10\mu\text{F}$  capacitor. The output should be bypassed with at least a  $10\mu\text{F}$  capacitor if using Type I compensation and  $22\mu\text{F}$  if using Type III compensation.

The same selection criteria apply for the buck-boost regulator input and output capacitors as described in the Buck Switching Regulator Input/Output Capacitor Selection section.

### PCB Layout Considerations

In order to deliver maximum charge current under all conditions, it is critical that the backside of the LTC3558 be soldered to the PC board ground.

The LTC3558 has dual switching regulators. As with all switching regulators, care must be taken while laying out a PC board and placing components. The input decoupling capacitors, the output capacitor and the inductors must all be placed as close to the pins as possible and on the same side of the board as the LTC3558. All connections must also be made on the same layer. Place a local unbroken ground plane below these components. Avoid routing noisy high frequency lines such as those that connect to switch pins over or parallel to lines that drive high impedance inputs.



## LTC3558

### TYPICAL APPLICATIONS

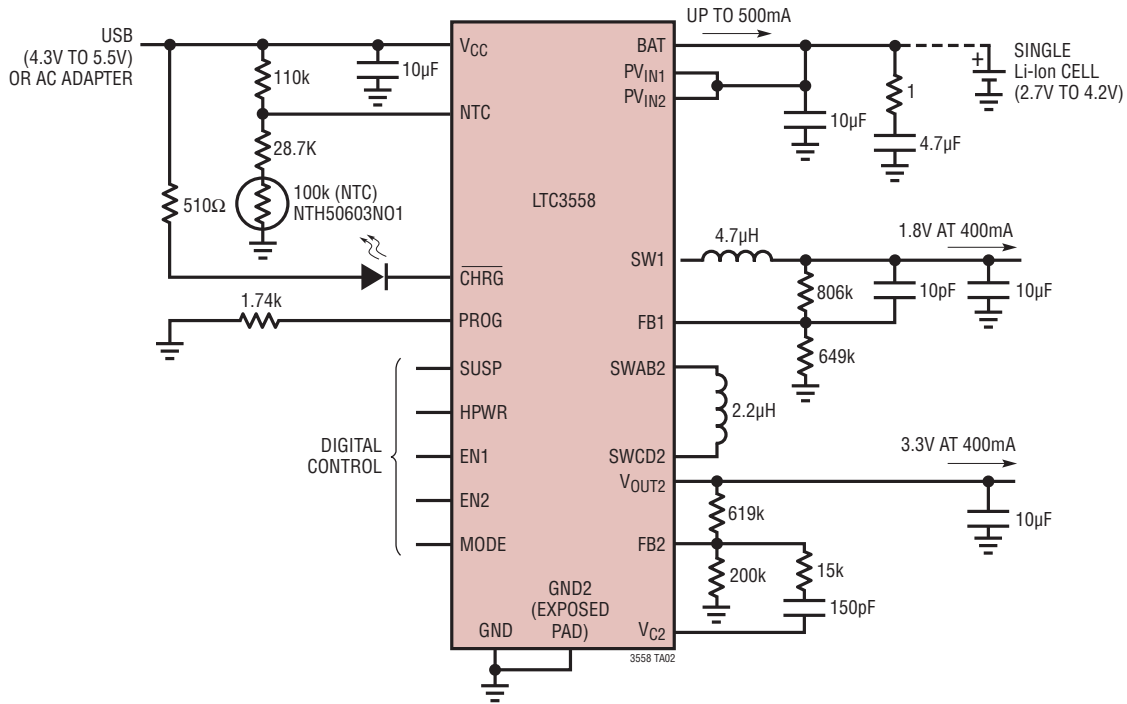


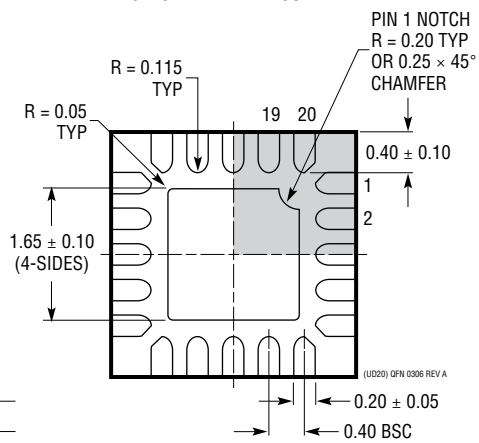
Figure 12. Li-Ion to 3.3V at 400mA, 1.8V at 400mA and USB-Compatible Battery Charger

As shown in Figure 12, the LTC3558 can be operated with no battery connected to the BAT pin. A 1Ω resistor in series with a 4.7μF capacitor at the BAT pin ensures battery charger stability. 10μF V<sub>CC</sub> decoupling capacitors are required for proper operation of the DC/DC converters. A three-resistor bias network for NTC sets hot and cold trip points at approximately 55°C and 0°C.

The battery can be charged with up to 950mA of charge current when powered from a 5V wall adaptor, as shown

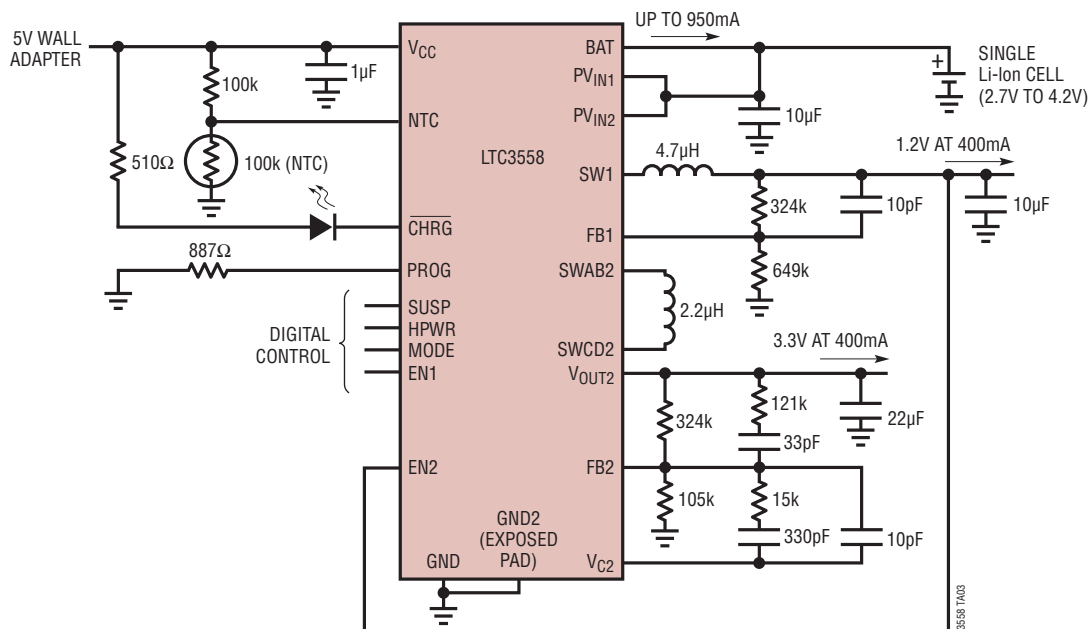
in Figure 13.  $\overline{\text{CHRG}}$  has a LED to provide a user with a visual indication of battery charge status. The buck-boost regulator starts up only after V<sub>OUT1</sub> is up to approximately 0.7V. This provides a sequencing function which may be desirable in applications where a microprocessor needs to be powered up before peripherals. A Type III compensation network improves the transient response of the buck-boost switching regulator.

**UD Package**  
**20-Lead Plastic QFN (3mm × 3mm)**  
 (Reference LTC DWG # 05-08-1720 Rev A)



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## TYPICAL APPLICATIONS



## RELATED PARTS

PART NUMBER	DESCRIPTION	COMMENTS
LTC3550	Dual Input USB/AC Adapter Li-Ion Battery Charger with Adjustable Output 600mA Buck Converter	Synchronous Buck Converter, Efficiency: 93%, Adjustable Output at 600mA, Charge Current: 950mA Programmable, USB Compatible, Automatic Input Power Detection and Selection
LTC3552	Standalone Linear Li-Ion Battery Charger with Adjustable Output Dual Synchronous Buck Converter	Synchronous Buck Converter, Efficiency: >90%, Adjustable Outputs at 800mA and 400mA, Charge Current Programmable Up to 950mA, USB Compatible, 5mm × 3mm DFN-16 Package
LTC3552-1	Standalone Linear Li-Ion Battery Charger with Dual Synchronous Buck Converter	Synchronous Buck Converter, Efficiency: >90%, Outputs 1.8V at 800mA and 1.575 at 400mA, Charge Current Programmable up to 950mA, USB Compatible
LTC3455	Dual DC/DC Converter with USB Power Manager and Li-Ion Battery Charger	Seamless Transition Between Input Power Sources: Li-Ion Battery, USB and 5V Wall Adapter, Two High Efficiency DC/DC Converters: Up to 96%, Full Featured Li-Ion Battery Charger with Accurate USB Current Limiting (500mA/100mA) Pin-Selectable Burst Mode Operation, Hot Swap™ Output for SDIO and Memory Cards, 4mm × 4mm QFN-24 Package
LTC3456	2-Cell, Multi-Output DC/DC Converter with USB Power Manager	Seamless Transition Between 2-Cell Battery, USB and AC Wall Adapter Input Power Sources, Main Output: Fixed 3.3V Output, Core Output: Adjustable from 0.8V to $V_{BATT(MIN)}$ , Hot Swap Output for Memory Cards, Power Supply Sequencing: Main and Hot Swap Accurate USB Current Limiting, High Frequency Operation: 1MHz, High Efficiency: Up to 92%, 4mm × 4mm QFN-24 Package
LTC3559	USB Charger with Dual Buck Regulators	Adjustable, Synchronous Buck Converters, Efficiency >90%, Outputs: Down to 0.8V at 400mA Each, Charge Current Programmable Up to 950mA, USB-Compatible, 3mm × 3mm QFN-16 Package
LTC4080	500mA Standalone Charger with 300mA Synchronous Buck	Charges Single-Cell Li-Ion Batteries, Timer Termination + C/10, Thermal Regulation, Buck Output: 0.8V to $V_{BAT}$ , Buck Input $V_{IN}$ : 2.7V to 5.5V, 3mm × 3mm DFN-10 Package

3558f



## **Monolithic Linear USB Battery Charger with High Efficiency Buck-Boost & Buck Converters**

MILPITAS, CA – May 20, 2008 – Linear Technology Corporation announces the LTC3558, an efficient, multi-function power management solution for handheld applications. The LTC3558 integrates a stand-alone Li-Ion/Polymer battery charger and two high efficiency synchronous regulators – one buck-boost and one buck – and is offered in a compact low-profile 3mm x 3mm QFN package. The linear battery charger can deliver up to 950mA charge current from a wall adapter supply, or up to 500mA charge current from a USB port. The LTC3558's stand-alone autonomous operation simplifies design, eliminating the need for an external microprocessor for charge termination. Both switching regulators are designed to operate over the Li-Ion/Polymer range of 2.7V to 4.2V while delivering output currents up to 400mA each.

The LTC3558's integrated synchronous buck regulator features 100% duty cycle operation, while the buck-boost regulator is capable of regulating its programmed output voltage (typically 3.3V) over the entire Li-Ion/Polymer operating range. The integrated low  $R_{DS(ON)}$  switches enable efficiencies as high as 92%, maximizing battery run time. In addition, Burst Mode<sup>®</sup> operation optimizes efficiency at light loads with a quiescent current of only 20uA for the buck-boost and 35uA for the buck (<1uA in shutdown for each). The high 2.25MHz switching frequency allows the utilization of tiny low cost capacitors and inductors less than 1mm in height. Furthermore, the regulators are stable with ceramic output capacitors, achieving very low output voltage ripple.

The LTC3558's battery charger contains a high degree of USB functionality, including 20%/100% full-scale charge current setting, a SUSP pin for shutdown/enable, and 4 different indication states on the /CHRG pin. The final battery float voltage is accurate to  $\pm 0.5\%$ . The charger's patented thermal regulation scheme maximizes the charge rate without the risk of overheating, while the NTC input allows temperature-qualified charging. To preserve battery

energy, the LTC3558 draws  $< 3\mu\text{A}$  from the battery in suspend mode. The charger is compatible with inputs up to 5.5V (7V absolute maximum transient for added robustness).

The LTC3558 is available from stock in a compact low-profile (0.75mm) 3mm x 3mm QFN-20 package. Pricing starts at \$2.35 each for 1,000-piece quantities.

**Photo Caption:** Multi-Function Linear Charger + Sync Buck-Boost + Sync Buck

### Summary of Features: LTC3558

- Complete Multi-Function PMIC: Linear Charger, Synchronous Buck-Boost & Buck Regulators

#### **Battery Charger**


- Charge Current Programmable up to 950mA from Wall Adapter Input
- Charges Directly from a USB Port with 20%/100% Current Select
- No External MOSFET, Sense Resistor or Blocking Diodes Needed
- Thermal Regulation Maximizes Charging Rate without Overheating
- Preset Battery Float Voltage with  $\pm 0.5\%$  Accuracy
- Standalone Autonomous Operation
- Charge Status Output with Multiple Indication States

#### **Switching Regulators**

- High Efficiency Synchronous Regulators: One Buck-Boost and One Buck
- Adjustable Output Voltage Range: Buck-Boost - 2.75V – 5.45V, Buck - Down to 0.8V
- Switching Regulator Output Currents: 400mA each
- 2.25MHz Constant Frequency Operation
- Thermally-Enhanced, Low Profile (0.75mm) 20-Lead 3mm x 3mm QFN Package

### About Linear Technology

Linear Technology Corporation, a manufacturer of high performance linear integrated circuits, was founded in 1981, became a public company in 1986 and joined the S&P 500 index of major public companies in 2000. Linear Technology products include high performance amplifiers, comparators, voltage references, monolithic filters, linear regulators, DC-DC converters, battery chargers, data converters, communications interface circuits, RF signal conditioning circuits, uModule<sup>TM</sup> products, and many other analog functions. Applications for Linear Technology's high performance circuits include telecommunications, cellular telephones, networking products such as optical switches, notebook and desktop computers, computer peripherals, video/multimedia, industrial instrumentation, security monitoring devices, high-end consumer products such as digital cameras and MP3 players, complex medical devices, automotive electronics, factory automation, process control, and military and space systems. For more information, visit [www.linear.com](http://www.linear.com).

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# DEMO CIRCUIT 1276B QUICK START GUIDE

## LTC3558EUD: Linear USB Battery Charger with Buck and Buck-Boost Regulators

### DESCRIPTION

Demonstration Circuit DC1276B is a Linear USB Battery Charger with Buck and Buck-Boost Converters featuring the LTC<sup>®</sup>3558EUD. The LTC3558EUD is a linear battery charger IC for Li-Ion/polymer battery applications, with a general purpose synchronous step-down switching regulator and a general purpose buck-boost regulator. For USB powered applications, the battery charge current can be limited to 500mA, by setting  $R_{\text{PROG}}$  to 1.74 k $\Omega$ . For non-USB powered applications, the charge current can be set as high as

950mA, by simply changing  $R_{\text{PROG}}$ . The buck and the buck-boost switching regulators can deliver up to 400mA load current, each. The LTC3558EUD is available in 20-pin (3mm  $\times$  3mm) QFN surface mount package.

Design files for this circuit board are available, call the LTC factory.

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### PERFORMANCE SUMMARY Specifications are at $T_A = 25^\circ\text{C}$

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
$V_{\text{CC}}$	Input voltage range		4.35		5.5	V
VFLOAT	BAT float voltage	Constant Voltage mode	4.15		4.23	V
IBAT	Battery charge current	Constant current mode, $R_{\text{PROG}} = 1.74\text{k}\Omega$ , HPWR=HI	0.46		0.5	A
VOUT1	Buck regulator output voltage	$\text{IOUT1} \leq 400\text{mA}$	1.17		1.23	V
VOUT2	Buck-Boost regulator output voltage	$\text{IOUT2} \leq 400\text{mA}$	3.27		3.33	V

### QUICK START PROCEDURE

Demo Circuit DC1276B is best evaluated using a Li-Ion or Li-Polymer battery. When using a battery simulator for evaluation, oscillations must be verified with a real battery at the same conditions because it is difficult to match the impedance of a real battery. Capacitor C10 was added to simulate the low impedance of a real battery. It will allow proper operation of the demo circuit with or without a battery and even with a battery simulator consisting of a power supply in parallel with a 3.6 Ohm resistor.

Refer to Figure 1 for the proper measurement equipment setup and jumper settings and follow the procedure below.

**NOTE.** When measuring the input or output voltage ripple, care must be taken to avoid a long ground lead on the oscilloscope probe. Measure the input or output voltage ripple by touching the probe tip directly across the  $V_{\text{CC}}$  or VOUT(x) and GND terminals. See Figure 2 for proper scope probe technique.

1. Set PS1 to 5.0V, and PS2 to 3.6V.
2. Observe AM1, AM4, VM2, VM3, VM4, VM5, and VM6.

# QUICK START GUIDE FOR DEMONSTRATION CIRCUIT DC1276B

## HIGH EFFICIENCY USB POWER MANAGER WITH BUCK AND BUCK-BOOST REGULATORS

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3. Set the HPWR jumper (JP1) to "20%". Observe AM1 and AM4.
4. Set the NTC jumper (JP3) to "EXT". Observe VM3. The "CHRG" LED (D1) should be blinking.
5. Set the HPWR jumper (JP1) to "100%", the SUSP jumper (JP2) to "OFF" and the NTC jumper (JP3) to "INT".
6. Set Ld1 to 400mA. Observe VM4 and AM2. Set Ld1 to 0mA.
7. Set Ld2 to 400mA. Observe VM5 and AM3. Set Ld2 to 0mA.
8. Set EN1 (JP4) and EN2 (JP5) to "OFF". Observe VM4 and VM5.

## OPERATING PRINCIPLES

The LTC3558 is composed of 3 major functional blocks working together: Battery Charger, Buck Regulator, and Buck-Boost Regulator.

### The Battery Charger

The battery charger is a linear Li-Ion battery charger that operates in constant current mode, until the battery voltage rises to approximately the FLOAT voltage, of 4.2V, and then the charger switches to constant voltage mode.

The charge current is programmed by the PROG (R6) resistor, and has been set to 500mA, on DC1276B, with a 1.74k $\Omega$  resistor. The HPWR pin is used to select 20% or 100% of the programmed charge current. The charge current delivered is nominally the programmed current, so if the application requires compliance with the USB specification of presenting a 100mA/500mA or **less** load, the nominal charge current must be set to accommodate the full distribution of actual charge currents.

The battery charger implements trickle charging, for initial battery voltages less than 2.9V. It also imple-

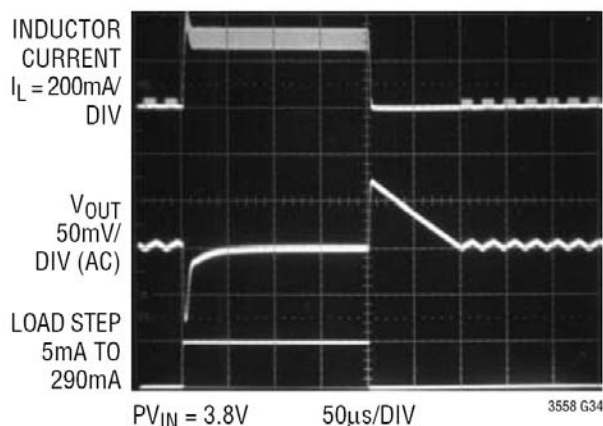
ments a charge termination timeout of 4 hours, and a bad cell charging timeout of 30 minutes. An NTC input is used to determine if the battery temperature is suitable for charging, too hot or too cold.

The state of charge, as well as any faults, is signaled with the  $\overline{\text{CHRG}}$  pin.

### Buck Regulator

The general purpose 400mA buck regulator is implemented as a current mode, synchronous rectifier regulator, operating at 2.25MHz. Step response is excellent and output ripple is very low.

#### Buck Regulator Transient Response, Pulse Skip Mode



### Buck-Boost Regulator

The general purpose 400mA buck-boost regulator is implemented as a voltage mode regulator, operating at 2.25MHz. A type three compensation is recommended for this regulator to achieve the best performance.

## APPLICATION INFORMATION

This demo circuit is designed to demonstrate the full capability of the device. Not all components are required in all applications. The critical circuit components are on the top of the board near the IC.

The VCC input capacitor network of C1 and R1 is used to dampen input source inductances that



commonly occur in laboratory setups with twisted leads and a bench power supply. When using a USB cable or adaptor cable this input damping network will likely not be required. Please note that the in-circuit capacitance of the specified 10uF, 0603 ceramic capacitor for C1 is approximately 5uF each at 5V.

Capacitor C9 is included to simulate a low impedance battery. It is especially helpful when testing the demo circuit with a battery simulator comprised of a power supply with a 3.6 Ohm power resistor across it. The leads connecting the power supply to the demo circuit should be a twisted pair to minimize lead inductance; although, even twisted pairs can introduce enough inductance into the circuit to turn on overshoot without damping resistor R17.

#### Power dissipation

The LTC3558 implements a linear battery charger with no pre-regulator. The battery charge current can be set as high as 0.95A, by choosing the appropriate PROG (R6) resistor.

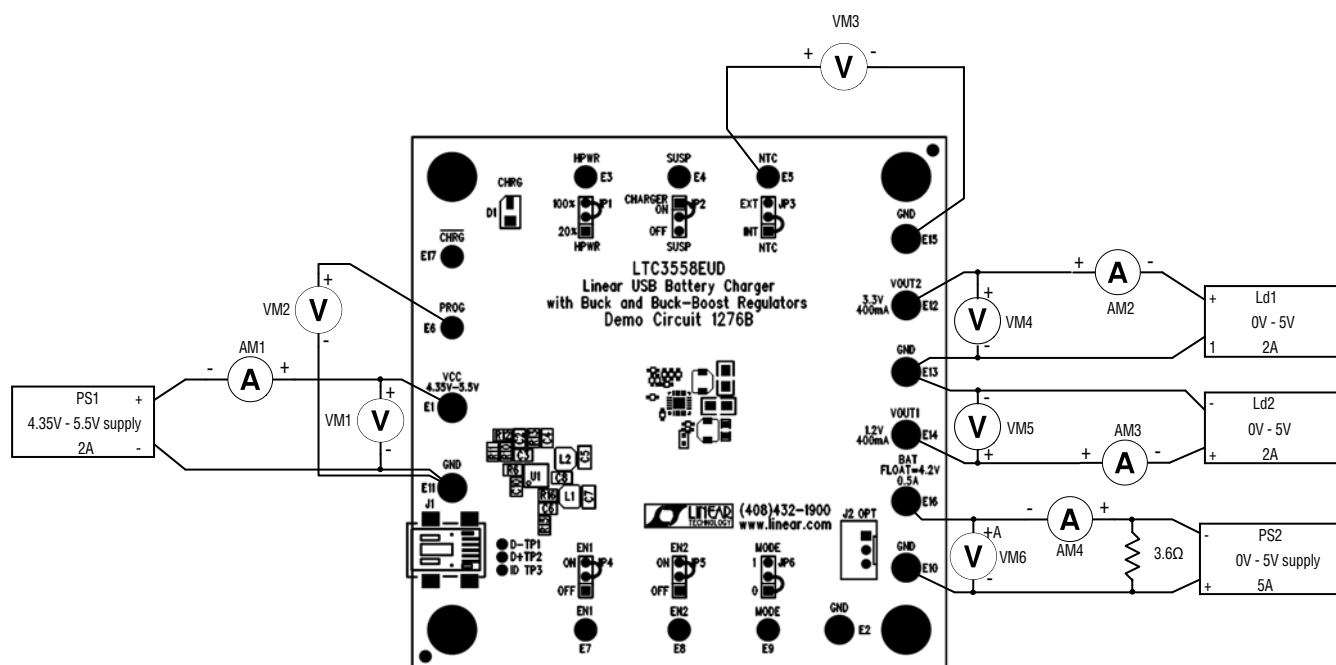
For a typical application of USB charging of a battery, VCC = 5V, BAT = 3V. The  $\theta_{JA}$  of the package is 68°C/W, and the maximum  $T_J$  is 125°C. Thus, for  $T_A(\text{max}) = 50^\circ\text{C}$  the maximum charge current without thermal regulation can be as high as 550mA.

If a higher charge current is desired, the PROG resistor (R6) can be changed. If the resultant power dissipation exceeds the package dissipation rating the LTC3558 will go into thermal regulation, and reduce charge current to an acceptable level.

# QUICK START GUIDE FOR DEMONSTRATION CIRCUIT DC1276B

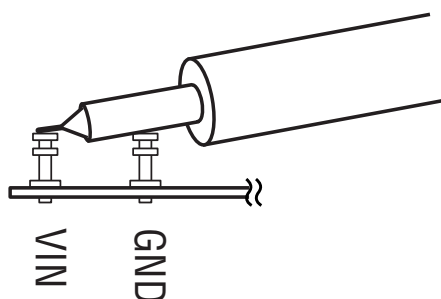
## HIGH EFFICIENCY USB POWER MANAGER WITH BUCK AND BUCK-BOOST REGULATORS

**LTC3558EUD**



Note: All connections from equipment should be Kelvin connected directly to the board pins which they are connected on this diagram and any input or output leads should be twisted pair.

**Figure 1. Proper Measurement Equipment Setup for DC1276B**



**Figure 2: Measuring Input or Output Ripple**

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## HIGH EFFICIENCY USB POWER MANAGER WITH BUCK AND BUCK-BOOST REGULATORS

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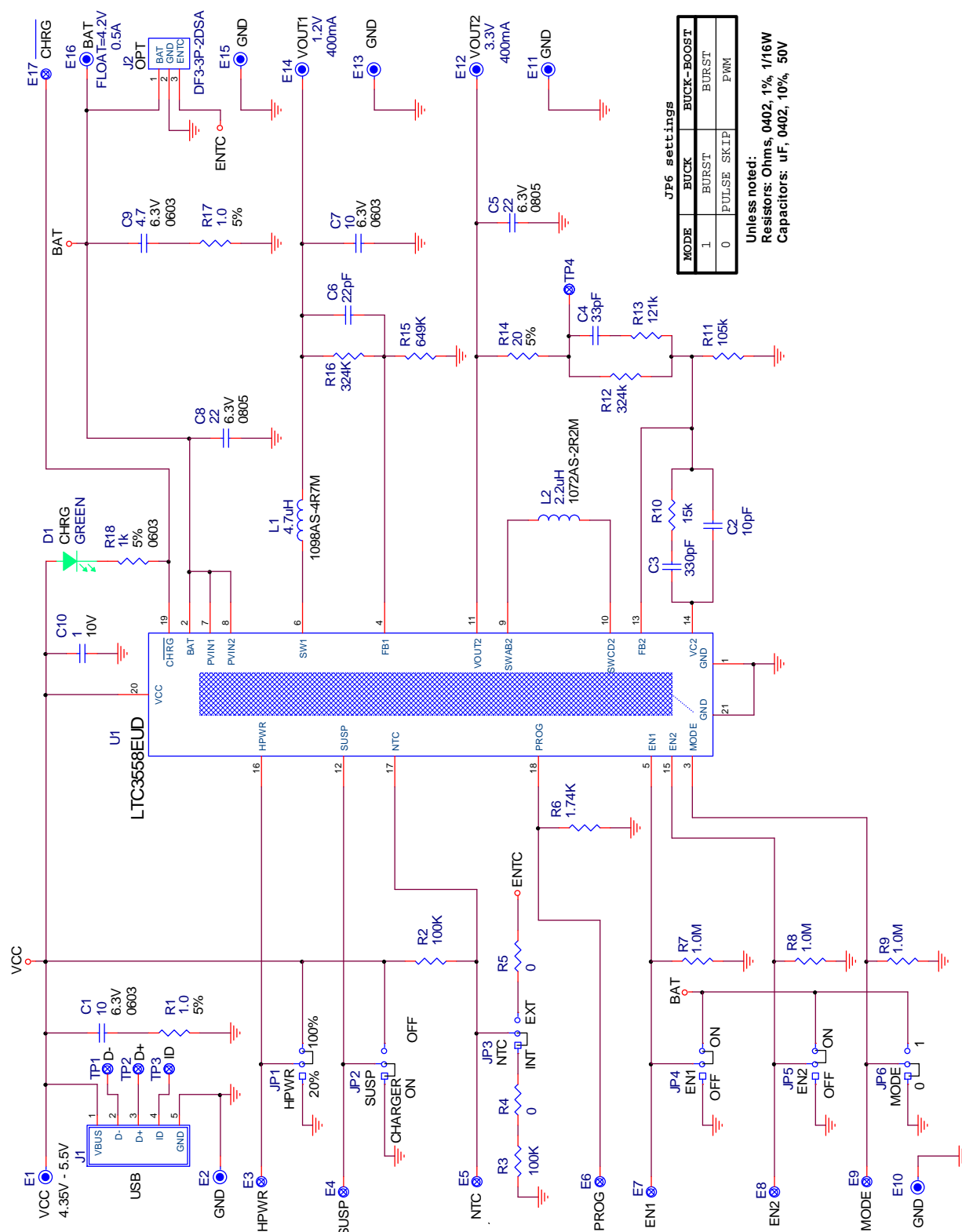


Figure 3: Circuit Schematic

# QUICK START GUIDE FOR DEMONSTRATION CIRCUIT DC1276B

## HIGH EFFICIENCY USB POWER MANAGER WITH BUCK AND BUCK-BOOST REGULATORS

### LTC3558EUD

	Qty	Reference	Part Description	Manufacture / Part #
REQUIRED CIRCUIT COMPONENTS:				
1	1	C2	CAP, CHIP, C0G, 10pF, ±0.5pF, 50V, 0402	VISHAY, VJ0402A100DXAA
2	1	C3	CAP, CHIP, BX, 330pF, ±5%, 50V, 0402	VISHAY, VJ0402X331JXAA
3	1	C4	CAP, CHIP, C0G, 33pF, ±5%, 50V, 0402	VISHAY, VJ0402A330JXAA
4	2	C5,C8	CAP, CHIP, X5R, 22µF, ±20%, 6.3V, 0805	MURATA, GRM21BR60J226ME39L
5	1	C6	CAP, CHIP, C0G, 22pF, ±5%, 50V, 0402	MURATA, GRM1555C1H220J
6	1	C7	CAP, CHIP, X5R, 10µF, ±20%, 6.3V, 0603	MURATA, GRM188R60J106ME47D
7	1	C10	CAP, CHIP, X5R, 1.0µF, ±10%, 10V, 0402	MURATA, GRM155R1A105KE15D
8	1	L1	IND, SMT, 4.7µH, 155mΩ, ±20%, 1.2A, 3.0mmX3.2mm	TOKO, 1098AS-4R7M
9	1	L2	IND, SMT, 2.2uH, 39mΩ, ±20%, 1.8A, 2.8mmX3.0mm	TOKO, 1072AS-2R2M
10	1	R6	RES, CHIP, 1.74kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW04021K74FKED
11	1	R10	RES, CHIP,15kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW040215K0FKED
12	1	R11	RES, CHIP, 105kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW0402105KFKED
13	2	R12,R16	RES, CHIP, 324kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW0402324KFKED
14	1	R13	RES, CHIP, 121kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW0402121KFKED
15	1	R15	RES, CHIP, 649kΩ, ±1%, 1/16W, 0402	VISHAY, CRCW0402649KFKED
16	1	U1	Linear USB Battery Charger with Buck and Buck-Boost Regulators	LINEAR TECH., LTC3558EUD
ADDITIONAL DEMO BOARD CIRCUIT COMPONENTS:				
1	1	C1	CAP, CHIP, X5R, 10µF, ±20%, 6.3V, 0603	MURATA, GRM188R60J106ME47D
2	1	C9	CAP, CHIP, X5R, 4.7µF, ±20%, 6.3V, 0603	MURATA, GRM188R60J475KE19D
3	1	D1	DIODE, LED, GREEN, SMT, 1206	PANASONIC, LN1351CTR
4	2	R1,R17	RES, CHIP, 1.0Ω, ±5%, 1/16W, 0402	VISHAY, CRCW04021R00JNED
5	2	R2,R3	RES, CHIP, 100kΩ, ±5%, 1/16W, 0402	VISHAY, CRCW0402100KFKED
6	2	R4,R5	RES, CHIP, 0Ω jumper, 1/16W, 0402	VISHAY, CRCW04020000Z0ED
7	3	R7,R8,R9	RES, CHIP, 1MEGΩ, ±1%, 1/16W, 0402	VISHAY, CRCW04021M00FKED
8	1	R14	RES, CHIP, 20Ω, ±1%, 1/16W, 0402	VISHAY, CRCW040220R0FNED
9	1	R18	RES, CHIP, 1kΩ, ±5%, 1/16W, 0603	VISHAY, CRCW06031K00JNED
HARDWARE FOR DEMO BOARD ONLY:				
1	1	J1	CONN, USB Mini-B	TYCO, 1734035-2
2	0	J2-OPT	CONN, Li-Ion battery	HIROSE, DF3-3P-2DSA
3	6	JP1,JP2,JP3,JP4,JP5,JP6	HEADER, 3 PINS, 2mm	SAMTEC, TMM-103-02-L-S
4	6	JP1,JP2,JP3,JP4,JP5,JP6	SHUNT 2MM	SAMTEC, 2SN-BK-G
5	9	E1,E2,E10,E11,E12,E13 E14,E15,E16	TURRET, 0.09 DIA	MILL-MAX, 2501-2-00-80-00-00-07-0
6	8	E3,E4,E5,E6,E7,E8,E9,E17	TURRET, 0.061 DIA	MILL-MAX, 2308-2-00-80-00-00-07-0

Figure 4: Bill of Materials