Battery Charger's Unique Input Regulation Loop Simplifies Solar Panel Maximum Power Point Tracking

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Advances in battery technology and device performance have made it possible to produce complex electronics that run for long periods between charges. Even so, for some devices, recharging the batteries by plugging into the grid is not possible. Emergency roadside telephones, navigation buoys, and remote weather monitoring stations are just a few applications that have no access to the power grid, so they must harvest energy from their environment.

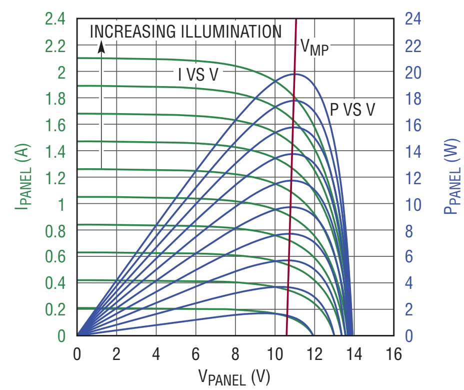


Figure 1. Current vs voltage and power vs voltage for a solar panel at a number of different illumination levels. The panel output voltage at the maximum power point (V_{MP}) remains relatively constant regardless of illumination level.

Solar panels have great potential as energy harvesting power sources—they just need batteries to store the harvested power and to provide carry-though during dark periods. Solar panels are relatively expensive, so extracting maximum power from the panels is paramount to minimizing the panel size. The tricky part is a balancing of solar panel size with required power. The characteristics of solar panels require careful management of the panel's output power versus load to effectively optimize the panel's output power for various lighting conditions.

For a given illumination level, a solar panel has a specific operating point that produces the maximum amount of power (see Figure 1). Maintaining this peak-power point during operation as lighting conditions change is called maximum peak power tracking (MPPT). Complex algorithms are often used to perform this function, such as varying the panel's load periodically while directly measuring panel output voltage and output current, calculating panel output power, then forcing the point of operation that provides the peak output power as illumination and/or temperature conditions change. This type of algorithm generally requires complex circuitry and microprocessor control.

There exists, however, an interesting relationship between the output voltage of a solar panel and the power that the panel produces. A solar panel output voltage at the maximum power point remains relatively constant regardless of illumination level. It follows that forcing operation of the panel such that the output voltage is maintained at this peak power voltage (V_{MP}) yields peak output power from the panel. A battery-charger can therefore maintain peak power transfer by exploiting this V_{MP} characteristic instead of implementing complex MPPT circuitry and algorithms.

In Depth

For an in-depth discussion of the maximum power point tracking feature of the LT3652, see "Designing a Solar Cell Battery Charger" in the December 2009 issue of *LT Magazine*. You can find this article and the LT3652 data sheet at www.linear.com/3652.

A FEW FEATURES OF THE LT3652 BATTERY CHARGER

The LT3652 is a complete monolithic step-down multi-chemistry battery charger that operates with input voltages as high as 32V (40V abs max) and charges battery stacks with float voltages up to 14.4V. The LT3652 incorporates an innovative input regulation circuit, which implements a simple and automatic method for controlling the charger's input supply voltage when using poorly regulated sources, such as solar panels. The LT3652HV, a high voltage version of the charger, is available to charge battery stacks with float voltages up to 18V.

The LT3652 is a versatile platform for simple and efficient solar-powered battery charger solutions, applicable to a wide variety of battery chemistries and configurations. The LT3652 is equally at home in conventionally powered applications, providing small and efficient charging solutions for a wide variety of battery chemistries and stack voltages.

Input Regulation Loop Maintains Peak Power Point for Solar Panels

The LT3652 input regulation loop linearly reduces the output battery charge current if the input supply voltage falls toward a programmed level. This closed-loop regulation circuit servos the charge current, and thus the load on the input supply, such that the input supply voltage is maintained at or above a programmed level. When powered by a solar panel, the LT3652 implements MPPT operation by simply programming the minimum input voltage level to that panel's peak power voltage, V_{MP}. The desired peak-power voltage is programmed via a resistor divider.

If during charging, the power required by the LT3652 exceeds the available power from the solar panel, the LT3652 input regulation loop servos the charge current lower. This might occur due to an increase in desired battery charge current or drop in solar panel illumination levels. In either case the regulation loop maintains the solar panel output voltage at the programmed V_{MP} as set by the resistor divider on VIN_REG.

The input regulation loop is a simple and elegant method of forcing peak power operation from a particular solar panel. The input voltage regulation loop also allows optimized operation from other types of poorly regulated sources, where the input supply can collapse during overcurrent conditions.

Integrated, Full-Featured Battery Charger

The LT3652 operates at a fixed switching frequency of 1MHz, and provides a constant-current/constant-voltage (CC/CV) charge characteristic. The part is externally resistor-programmable to provide charge current up to 2A, with charge-current accuracy of ±5%. The IC is particularly suitable for the voltage ranges associated with popular and inexpensive "12V system" solar panels, which typically have open-circuit voltages around 25V.

The charger employs a 3.3V float voltage feedback reference, so any desired battery float voltage from 3.3V to 14.4V (or up to 18V with the LT3652HV) can be programmed with a resistor divider. The float-voltage feedback accuracy for the LT3652 is ±0.5%. The wide LT3652 output voltage range accommodates many battery chemistries and configurations, including up to three Li-ion/polymer cells in series, up to four $LiFePO_4$ (lithium iron phosphate) cells in series, and sealed lead acid (SLA) batteries containing up to six cells in series. The LT3652HV, a high-voltage version of the charger, is also available. The LT3652HV operates with input voltages up to 34V and can charge to float voltages of 18V, accommodating 4-cell Li-ion/polymer or 5-cell $LiFePO_4$ battery stacks.

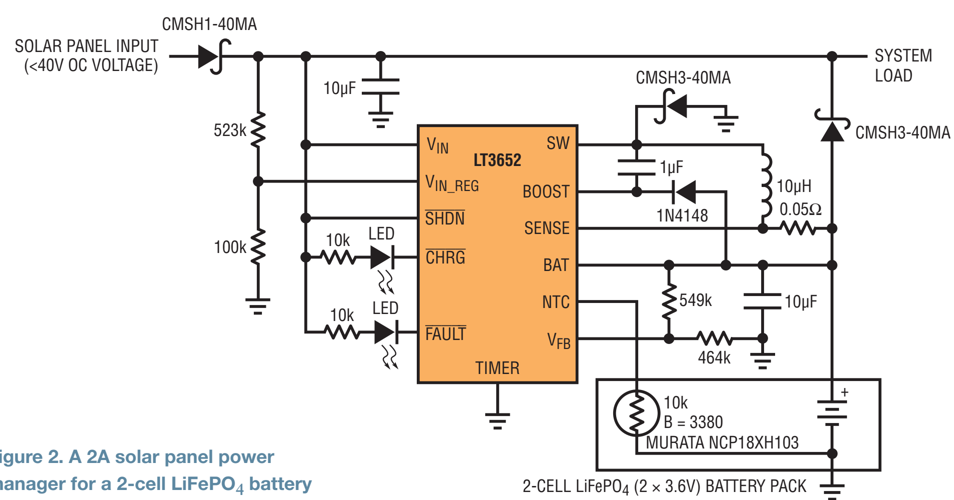


Figure 2. A 2A solar panel power manager for a 2-cell $LiFePO_4$ battery with 17V peak power tracking

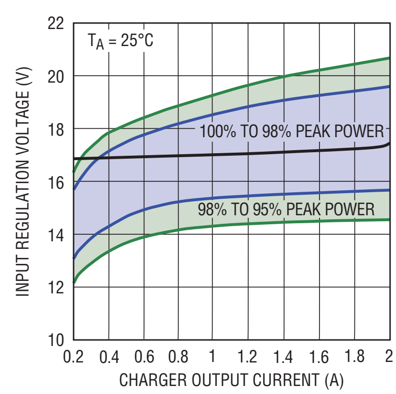


Figure 3. A 17V input voltage regulation threshold tracks solar panel peak power to greater than 98%

The LT3652 incorporates an innovative input regulation circuit, which implements a simple and automatic method for controlling the charger's input supply voltage when using poorly regulated sources, such as solar panels.

The LT3652 contains a programmable safety timer used to terminate charging after a desired time is reached. Simply attaching a capacitor to the TIMER pin enables the timer. Shorting the TIMER pin to ground configures the LT3652 to terminate charging when charge current falls below 10% of the programmed maximum (C/10), with C/10 detection accuracy of ±2.5%. Using the safety timer for termination allows top-off charging at currents less than C/10. Once charging is terminated, the LT3652 enters a low-current (85µA) standby mode. An auto-recharge feature starts a new charging cycle if the battery voltage falls 2.5% below the programmed float voltage. The LT3652 is packaged in low-profile, 12-lead 3mm × 3mm DFN and MSOP packages.

Energy Saving Low Quiescent Current Shutdown

The LT3652 employs a precision-threshold shutdown pin, allowing simple implementation of undervoltage lockout functions using a resistor divider. While in low-current shutdown mode, the LT3652 draws only 15µA from the input supply. The IC also supports temperature-qualified charging by monitoring battery temperature using a single thermistor attached to the part's NTC pin. The device has two binary coded open-collector status pins that display the operational state of the LT3652 battery charger, CHRG and FAULT. These status pins can drive LEDs for visual signaling of charger status, or be used as logic-level signals for control systems.

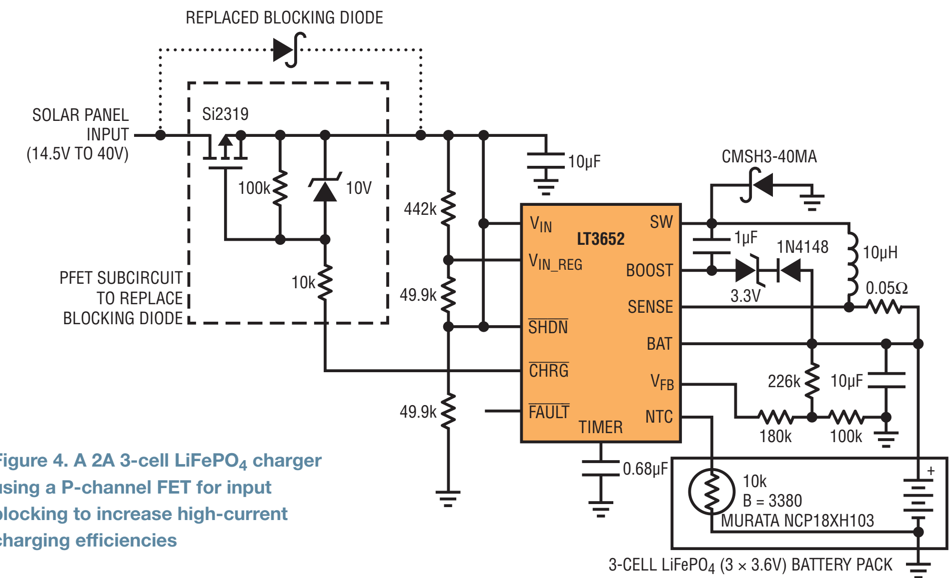
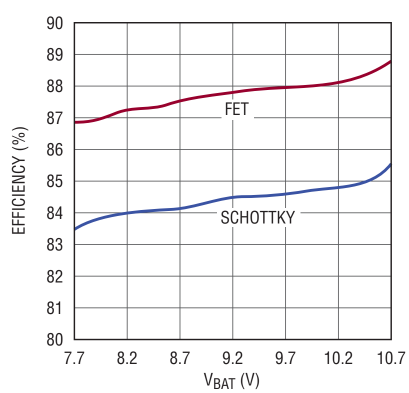


Figure 4. A 2A 3-cell $LiFePO_4$ charger using a P-channel FET for input blocking to increase high-current charging efficiencies

SIMPLE SOLAR POWERED BATTERY CHARGER

Figure 2 shows a 2A 2-cell $LiFePO_4$ battery charger with power path management. This circuit provides power to the system load from the battery when the solar panel is not adequately illuminated and directly from the solar panel when

Figure 5. Comparative efficiencies for blocking Schottky diode vs blocking FET as battery voltage rises for 15V to 10.8V 3-cell $LiFePO_4$ charger



the power required for the system load is available. The input voltage regulation loop is programmed for a 17V peak power input panel. The charger uses C/10 termination, so the charge circuit is disabled when the required battery charge current falls below 200mA. This LT3652 charger also uses two LEDs that provide status and signal fault conditions. These binary-coded pins signal battery charging, standby or shutdown modes, battery temperature faults and bad battery faults.

The input voltage regulation point is programmed using a resistor divider from the panel output to the VIN_REG pin. Maximum output charge current is reduced as the voltage on the solar panel output collapses toward 17V, which corresponds to 2.7V on the VIN_REG pin. This servo loop thus acts to dynamically reduce the power requirements of the charger system to the maximum

When powered by a solar panel, the LT3652 implements maximum power point tracking (MPPT) operation by simply programming the minimum input voltage level to that panel's peak power voltage, V_{MP}. The specific desired peak-power voltage is programmed via a resistor divider.

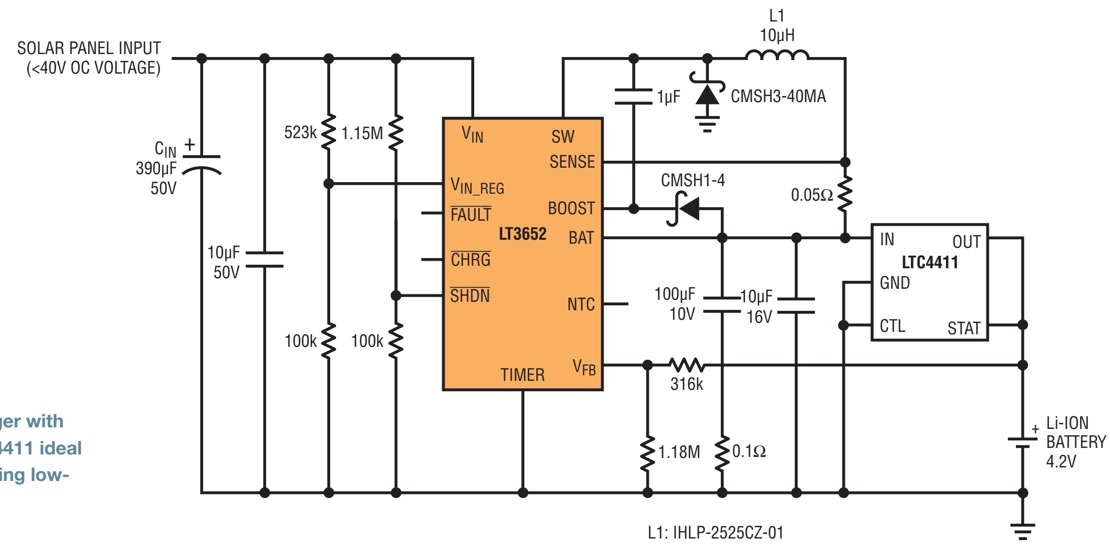


Figure 6. A solar powered, 2A Li-ion charger with ideal diode output pass element; the LTC4411 ideal diode IC prevents reverse conduction during low-light conditions

power that the panel can provide, maintaining solar panel power utilization close to 100%, as shown in Figure 3.

WANT BETTER EFFICIENCY? REPLACE THE BLOCKING DIODE WITH A BLOCKING FET

The LT3652 requires a blocking diode when used with battery voltages higher than 4.2V. The voltage drop across this diode creates a power loss term that reduces charging efficiency. This term can be greatly reduced by replacing the blocking diode with a P-channel FET, as shown in Figure 4.

Figure 4 shows a 3-cell $LiFePO_4$ 2A charger with a float voltage of 10.8V. This charger has an input voltage regulation threshold of 14.5V and is enabled by the SHDN pin when $V_{IN} \geq 13V$. Charge cycle termination is controlled by a 3-hour timer cycle. The blocking diode normally used in series with the input supply for reverse voltage protection is replaced by a FET. A 10V Zener diode clamp is used to prevent exceeding the FET maximum V_{GS}. If the specified V_{IN} range does not exceed the maximum V_{GS} of the input FET, this clamp is not required.

During the high-current charging period of a normal charge cycle (I_{CHG} > C/10), the $\overline{CHRG}$ status pin is held low. In the charger shown in Figure 4, this $\overline{CHRG}$ signal is used to pull the gate of the blocking FET low, enabling a low-impedance power supply path that eliminates the blocking diode drop to improve conversion efficiency. Figure 5 shows that the addition of this blocking FET improves efficiency by 4% compared to operation with a blocking Schottky diode.

Should the timer be used for termination, the body diode of the FET provides a conduction path once charge currents of < C/10 is achieved, and the $\overline{CHRG}$ pin becomes high-impedance. If desired, a blocking Schottky diode can be left in parallel with the blocking FET to improve conversion efficiency during the top-off portion of the timer-controlled charge cycle. Use of a FETKEY as the blocking element also increases top-off efficiency.

SCARED OF THE DARK? USE AN IDEAL DIODE FOR LOW-LIGHT APPLICATIONS

When the LT3652 is actively charging, the IC provides an internal load onto the switching loop to ensure closed-loop operation during all conditions. This is accomplished by sinking 2mA into the BAT pin whenever a charging cycle is active. In a solar-panel-powered battery charger, low-light conditions can make the input solar panel voltage collapse below the input regulation threshold, causing

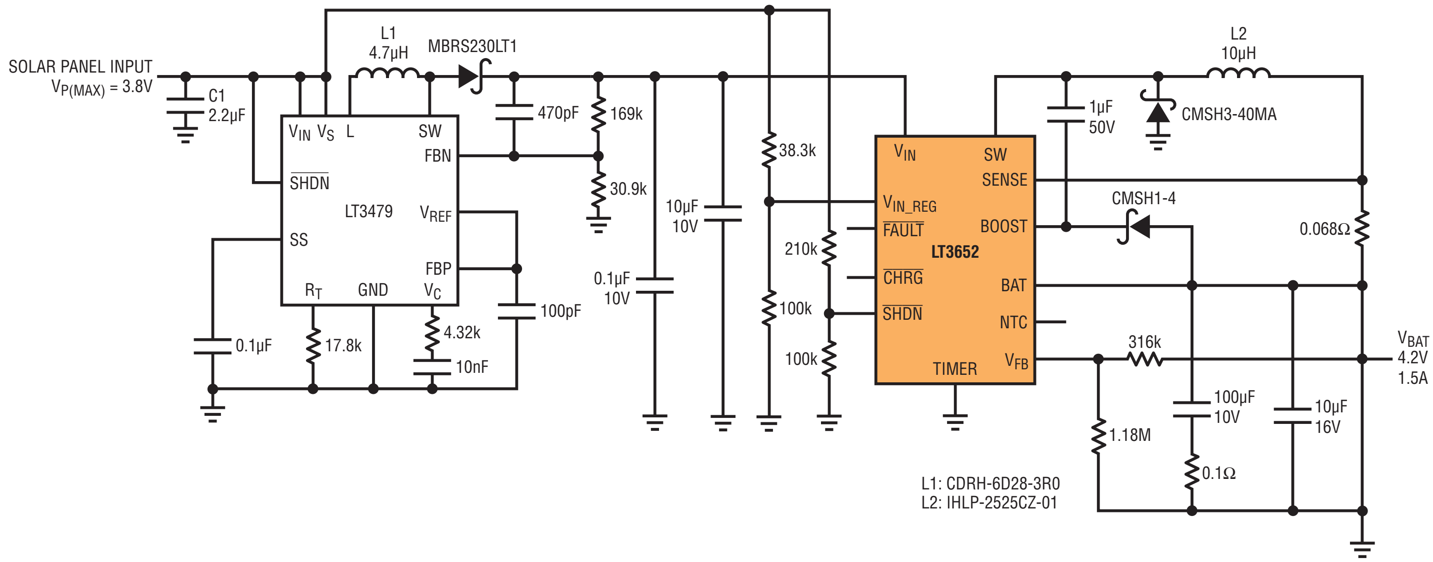


Figure 7. Low-voltage solar panel powers 1.5A single cell Li-ion buck/boost battery charger. The LT3479 boosts the solar panel's 3.8V output to operate an LT3652 charger. The LT3652's closed loop operation includes the boost converter, thus regulating the LT3479's input to the solar panel's V_{MP} of 3.8V.

output charge current to be reduced to zero. If the charger remains enabled during this condition (i.e., the panel voltage remains above the UVLO threshold), the internal battery load results in a net current drain from the battery. This is undesirable for obvious reasons, but this condition can be eliminated by incorporating a unidirectional pass element that prevents current backflow from the battery.

Linear Technology makes a high-efficiency pass element IC, the LTC4411 ideal diode, which has an effective forward drop close to zero. The effect on overall charger efficiency and final float voltage is negligible due to the extremely low forward drop during conduction.

Figure 6 shows an LT3652 solar-powered battery charger that employs low-light reverse protection using an LTC4411 ideal-diode IC. During a low light condition, should the panel voltage collapse below the input regulation threshold, the LT3652 reduces battery charge current to zero. In the case where the input voltage remains above the UVLO threshold, the charger remains enabled but is held in a zero charge current state. The LT3652 attempts to sink 2mA into the BAT pin; however, the LTC4411 prevents reverse conduction from the battery.

NEED TO STEP-UP? NO PROBLEM. A 2-STAGE BUCK-BOOST BATTERY CHARGER

The LT3652 can be used for step-up and step-up/step-down charger applications by incorporating a front-end step-up DC/DC converter. The front-end converter generates a local high-voltage supply for the LT3652 to use as an input supply. The LT3652 input regulation loop functions perfectly when wrapped around both converters.

Figure 7 shows a low-voltage solar panel powered 1.5A single-cell Li-ion charger with a 4.2V float voltage. This charger is designed to operate from a solar panel that has a peak power voltage of 3.8V.

An LT3479 switching boost converter running at 1MHz is used on the front-end to create an 8V supply, which is used to power the LT3652. This charger operates with input voltages as low as the input regulation threshold of 3.8V, up to 24V, the maximum input voltage for the LT3479. When input voltages approach 8V (or higher), the LT3479 boost converter no longer regulates, ultimately operating at 0% duty cycle and effectively shorting the input supply through the pass Schottky diode to the LT3652. Because the input regulation loop monitors the input to the LT3479, when the input voltage collapses toward the input regulation threshold, the LT3652 scales back charge current, reducing the current requirements of the LT3479 boost converter. The input voltage servos to the regulation point, with the boost converter and LT3652 charger combination extracting the peak power available from the solar panel.

NEED MORE CHARGE CURRENT? USE MORE LT3652s

Multiple LT3652 chargers can be used in parallel to produce a charger that exceeds the charge current capability of a single LT3652. In the application shown in Figure 8, three 2A LT3652 charger networks are connected in parallel to yield a 6A 3-cell Li-ion charger with a float voltage of 12.3V that uses C/10 termination. This charger is solar power compatible, having an input regulation threshold of 20V. This charger also implements an input blocking FET to increase charging efficiencies.

The three LT3652 charger ICs share a common float voltage feedback network

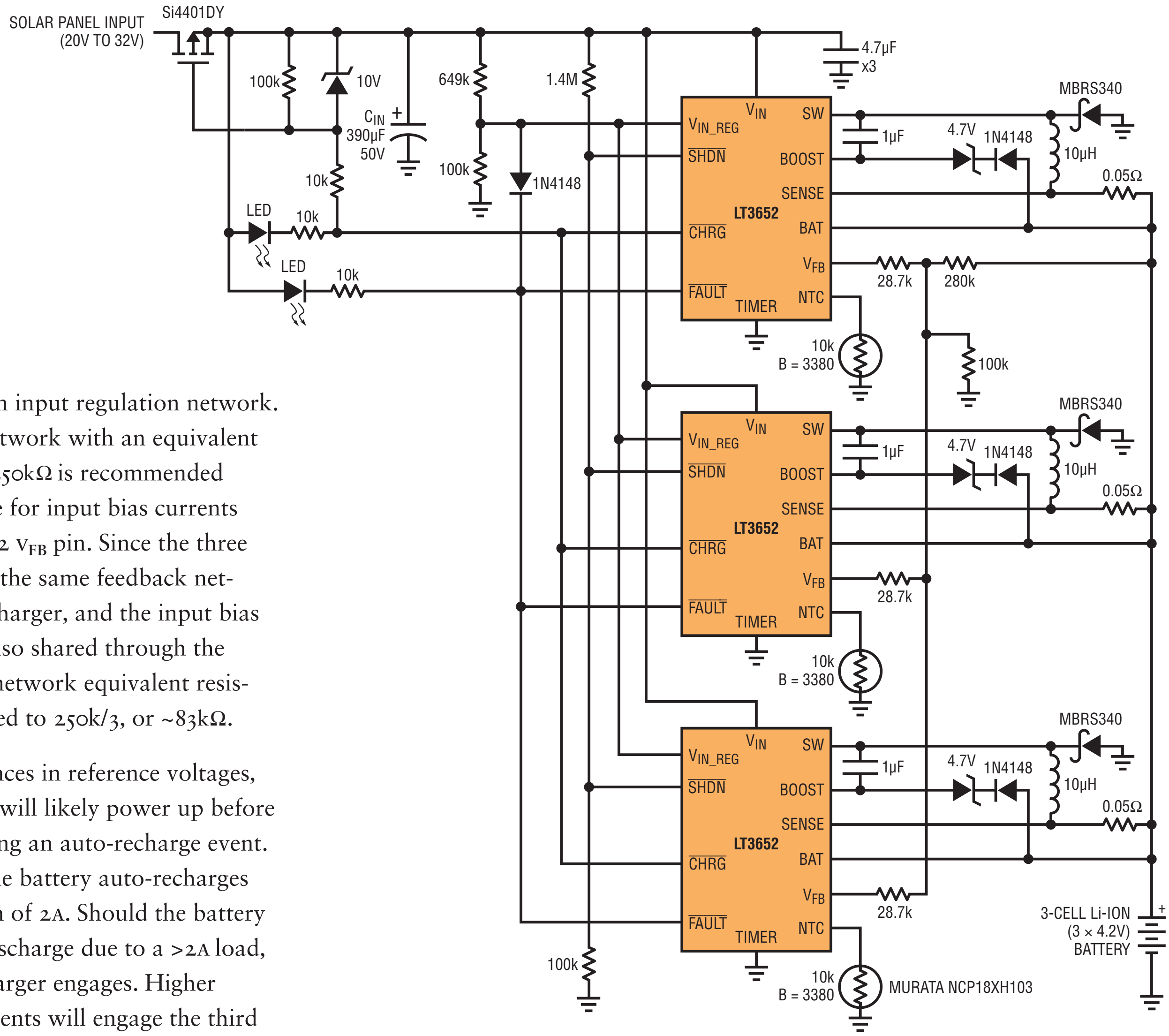


Figure 8. A 6A 3-cell Li-ion battery charger using three LT3652 charger ICs

and a common input regulation network. A feedback network with an equivalent resistance of 250kΩ is recommended to compensate for input bias currents into the LT3652 V_{FB} pin. Since the three LT3652s share the same feedback network in this charger, and the input bias currents are also shared through the network, the network equivalent resistance is reduced to 250k/3, or ~83kΩ.

Due to tolerances in reference voltages, one of the ICs will likely power up before the other during an auto-recharge event. In this case, the battery auto-recharges at a maximum of 2A. Should the battery continue to discharge due to a >2A load, the second charger engages. Higher discharge currents will engage the third charger IC, allowing the charger to produce the full 6A system charge current. The $\overline{\text{CHRG}}$ pins on all of the LT3652s are tied together to enable the input blocking FET, so the FET is low-impedance regardless of which order the ICs auto-restart.

The NTC and status functions are shared by all three LT3652s, with each IC using a dedicated NTC thermistor. The open collector status pins of the ICs are shorted together, so engaging any or all of the individual chargers lights the $\overline{\text{CHRG}}$ status indicator. Likewise, an NTC fault in any of the ICs lights the $\overline{\text{FAULT}}$ status indicator. The individual LT3652 NTC functions are slaved to each other via a diode connected from the common $\overline{\text{FAULT}}$ pins to the common VIN_REG pins of all three ICs. This diode pulls the VIN_REG pin below the VIN_REG threshold should any of the ICs trigger an NTC fault, which disables all output charge current until the temperature fault condition is relieved.

CONCLUSION

The LT3652 is a versatile platform for simple and efficient solar-powered battery charger solutions, applicable to a wide variety of battery chemistries and configurations. The LT3652 is equally at home in conventionally powered applications, providing small and efficient charging solutions for a wide variety of battery chemistries and stack voltages.

Solar-powered charger solutions maintain panel utilization close to 100%, reducing solution costs due to minimized panel area. The compact size of the IC, coupled with modest external component requirements, allows construction of stand-alone charger systems that are both tiny and inexpensive, providing a simple and efficient solution to realize true grid-independence for portable electronics. ■