makerPower™
MPPT Solar Charger

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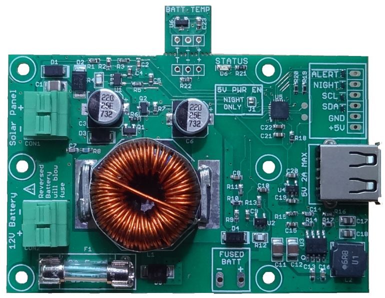


Introduction

The makerPower charger is designed to provide power to IOT-class devices (Arduino type through Raspberry Pi 3 type) in a remote, solar-powered environment. It manages charging a 12V AGM lead acid battery from common 36-cell 12V solar panels. It provides 5V power output at up to 2A for systems that include sensors or communication radios (although designed for average power consumption of 500 mA or less). Optimal charging is provided through a dynamic perturb-and-observe maximum power-point transfer converter (MPPT) and a 3-stage (BULK, ABSORPTION, FLOAT) charging algorithm. A removable temperature sensor provides temperature compensation. Operation is plug&play although additional information and configuration may be obtained through a digital interface.

Features

- Reverse Polarity protected solar panel input with press-to-open terminal block
- Fused battery input with press-to-open terminal block
- Maximum 2A at 5V output on USB Type A power output jack and solder header
- Automatic low-battery disconnect and auto-restart on recharged battery
- Temperature compensation sensor with internal sensor fallback
- Status LED indicating charge and power conditions, fault information
- I2C interface for detailed operation condition readout and configuration parameter access
- Configurable battery charge parameters
- Status signals for Night detection and pre-power-down alert
- Night-only operating mode (switch 5V output on only at night)
- Watchdog functionality to power-cycle connected device if it crashes or for timed power-down periods

Specification

MPPT Algorithm

The charger implements a modified version of the perturb and observe (P&O) MPPT algorithm. It controls a charge buck converter that reduces the solar panel voltage to the battery voltage in order to keep the solar panel voltage near the maximum power point (solar panel MPPT voltage). It does this by varying the solar panel MPPT voltage, measuring the power and constantly adjusting the solar panel MPPT voltage to try to maximize the power output of the solar panel (which translates into the maximum charge current to the battery). It uses variable voltage step sizes based on the current power output to increase accurate detection of power changes at low power levels.

Initially when starting a charge cycle and once every ten minutes the charger executes a scan function where it varies the output of the buck converter across the range from battery voltage to solar panel open circuit voltage and finds the current maximum power point to seed the P&O algorithm.

Charge Algorithm

The charge system uses a 3-state algorithm consisting of Bulk, Absorption and Float charge states.

1. Bulk Charge allows the maximum current into the battery until it reaches the bulk/absorption charge threshold voltage at which point the charger enters Absorption Charge state.
2. Absorption Charge constantly adjusts the charge buck converter to try to keep the battery at the bulk/absorption charge threshold voltage until the charge current falls off to less than 300 mA at which point the charger enters Float Charge state.
3. Float Charge constantly adjusts the charge buck converter to try to keep the battery at the float charge threshold voltage until solar power falls off at the end of the day.

The charger initiates a charge when the solar panel voltage exceeds 18V. The charger will remain in the Bulk/Absorption charge states a maximum of 10 hours before transitioning to the Float charge state. It transitions to a non-charging idle state after 15 seconds of low-power production from the solar panel (power less than 100 mW).

Solar Panel
Standard "12 volt" 36-cell (22V max open circuit voltage, 18V typical maximum power point transfer point) solar panel. Designed for 10-35 W panels (depending on load and battery). Maximum current consumption from panel is limited to 2A so higher current output panels may be connected to increase solar production in non-optimal conditions. Maximum input voltage must be 25V or less.

Charging is initiated when the open circuit (unloaded) voltage rises above 18V. Charging is terminated when the power output from the solar panel falls below 100 mW.

Battery
Charger default charge voltage thresholds are set for AGM-style lead acid batteries (e.g. UPS batteries) with a maximum charge current of 2.75A or less supporting batteries from about 7Ah to 18Ah (larger batteries may be supported subject to loading and charge conditions). Default bulk/absorption voltage is 14.7 volts and default float voltage is 13.65 volts. Other lead acid battery types may be supported by configuring appropriate bulk/absorption and float charge parameters in the charger via the I2C interface.

The 5V output is disabled when the battery voltage falls below 11.5 volts and is re-enabled when the battery voltage rises above 12.5 volts. These voltage levels may be adjusted in the charger via the I2C interface.

An on-board fast-acting 3A fuse provides protection. It will blow if the battery is connected with the polarity reversed or if the Fused Batt 12VDC output is shorted.

The charger puts a burden of about 6 mA on the battery whenever connected.

—WARNING—
BE VERY CAREFUL NOT TO SHORT A 12V LEAD ACID BATTERY - THEY ARE CAPABLE OF DUMPING HUNDREDS OF AMPS AND THE RISK OF FIRE OR INJURY IS HIGH!

5V Output
The 5V regulated output voltage is available on a USB Type A jack or Expansion Port. It is normally available anytime the battery is connected and above the low-voltage cut-off voltage. It is capable of supplying up to 2A current although the system is designed for smaller average operating currents (see the Operating Notes on sizing solar panels and batteries). The additional capacity is designed to be used under application control for things like long-distance radio communication.

A buck-mode switching converter is used to convert the battery voltage to the regulated 5V output. Its efficiency (η) varies with load current as shown below for a typical set of load currents.

- η = 62% for I = 20mA (Arduino)
- η = 78% for I = 50 mA
- η = 86% for I = 100 mA (Raspberry Pi Zero)
- η = 90% for I = 200 mA
- η = 92% for I = 350 mA (Raspberry Pi 3)
- η = 93% for I = 500 mA
- η = 92% for I = 1000 mA

—WARNING—
The 5V output is not short-circuit protected and a short may damage electronics in the charger.

Status LED
The Status LED indicates fault and operating conditions. Fault conditions have priority.

Fault Conditions (blinks every 5 seconds)

- Two repeating short blinks : Bad Battery connected. Battery voltage is less than 10.5 volts.
- Three repeating short blinks : External temperature sensor is disconnected.
- Four repeating short blinks : Temperature exceeds charge range (-20°C - 50°C). Charging is disabled.

Operating Conditions

- One short blink every 10 seconds : Output power disabled because of low-battery and the system is not currently charging.
- One short blink every 5 seconds: Output power is enabled and the system is not currently charging.
- Pulsing : Charging. Pulse brightness indicates charging power level.

Temperature Sensor
The charger contains two temperature sensors. The external temperature sensor is a small chip (U6) located on the break-off portion of the PCB. The internal temperature sensor is on-board the charger's micro-controller (U5). The charger will use the external temperature sensor to adjust (compensate) the battery charge voltage levels. It will use the internal temperature sensor if it detects that the external sensor is missing (disconnected).

The temperature sensors should be positioned to measure the approximate battery temperature. Typically it is adequate for the PCB to be adjacent to the battery. However if conditions cause the battery temperature to vary differently than the charger PCB, the external temperature sensor may be "cut-away" from the main PCB by using a fine saw to saw along the perforated lines (take a lot of care not to damage any other part of the PCB). It is then reconnected using three small gauge wires soldered between the header on the separate temperature sensor portion and the main charger PCB ("T" to "T," "-" to "-", and "+" to "+"). In this case the temperature sensor should be mounted near one of the battery terminals (but electrically isolated from it). The wire length should be two feet (0.6m) or less and braided together if possible to prevent noise injection.

The charger uses the following temperature compensation values from the default at 25°C.

- -30 mV/°C during bulk/absorption charging
- -18.8 mV/°C during float charging

Both temperature sensors are only accurate to within +/- 5°C over the entire operating temperature range.

<u>Jumper</u>
Bridging the "Night Only" solder jumper configures the charger to only enable the 5V output at night. Night is detected five minutes after the solar panel voltage falls below 3.5V. Night is ended when the solar panel voltage exceeds 3.5V. The solder jumper can be bridged using a soldering iron to deposit a small blob of solder between the two pads. It can be un-bridged by using solder-wick to remove the solder or dragging a fine tip between the two pads after applying flux to cause the solder to separate into two blobs. Take care to use a fine soldering iron tip and not rip up the jumper pads.

<u>Expansion Port</u>
The expansion port allows the user's application to interface with the charger. It may be used to directly wire data and power to a single board computer such as an Arduino or Raspberry Pi. It consists of three sets of signals: Power, I2C and Status Signals. Its use is optional, however. The user may simply connect their device to the USB jack and the charger will manage its own operation independently.

Power provides +5 volts at up to 2A and a common ground (used as a reference for both power and data).

The I2C interface is designed for 3.3V logic with a maximum clock rate of 100 kHz (see the important note about operating with a Raspberry Pi below in the I2C Interface section). It includes two 10k-ohm pull-up resistors to an on-board 3.3V power rail. It may be connected to a 5V device as long as that device does not include pull-up resistors to 5V (for example a 5V Arduino).

The Status Signals include two 3.3V logic signals. ALERT is active low and is asserted 60 seconds prior to the 5V output being disabled due to a low-battery or night condition (if the jumper is bridged). It is designed to give warning to the user's application to perform actions like a controlled shutdown prior to power failing without requiring use of the I2C interface. ALERT remains asserted low while power is disabled to avoid a condition where it may provide phantom power to the user's application through the GPIO port it is connected too. NIGHT is active low and asserted when the charger detects the night condition (solar panel below 3.5V for five minutes). NIGHT may be driven high while power is disabled so care should be taken to make sure it cannot supply phantom power if it is connected to the user's application through a GPIO port (better to use the I2C interface to get night status).

Short wires (typically less than one foot) should be used to connect the Expansion Port to the user's device. The data signals should only be connected to logic ports on the user's device although ALERT and NIGHT can be used as the gate signal to a small low-threshold N-channel MOSFET for switching higher currents (NIGHT could be used to switch on 12V LEDs connected to the Fused Batt 12VDC this way).

<u>Fused Batt 12VDC</u>
This output provides an output derived directly from the battery. It can be used to power higher-voltage devices such as LED lights or a DC-DC converter (possibly under control of the user's application through an external switch). Current on this output, along with current consumed by the charger and the 5V output, is measured by the charger.

<u>Chg Cfg</u>
Five resistors are left unstuffed. They are connected to the USB Jack data pins and can be used to configure maximum charge levels simulating some inexpensive USB chargers. What resistor locations should be stuffed and the values depends on the type of charger being simulated and a full description is beyond this document. More information may be found at the following web address.

https://electronics.stackexchange.com/questions/123172/what-is-the-ideal-way-to-handle-data-pins-d-and-d-on-a-usb-power-adapter-to-be

Operating Notes
Connect the battery before connecting the solar panel.

The charger will not operate without a battery. It will not charge unless the battery voltage exceeds 10.5V. It will shut down if the battery is removed.

The battery should be selected based on the load and the maximum time the load should operate without charging. It is ideal to limit repeated discharges to 70% of the battery capacity to maximize its life although occasional deeper discharges should not significantly harm it. A system configured with a lightly loaded Raspberry Pi 3 requires about 125 mA @ 12.5V (1.6W) from the battery. This system will require about 3A per 24 hours of operation. This is about 20% of a 15 Ah battery and 16.7% of a 18 Ah battery but 43% of a 7 Ah battery. A system with an 18 Ah battery could run for two days without significant solar charging while keeping the battery above 70% discharge. On the other hand a system using an Arduino or Particle SBC could easily run from a 7 or 9 Ah battery.

The solar panel should be sized according to the battery and amount of sun expected. Solar panels typically list the optimum current (for example 2 A at 17.5 volts for an AcoPower 35 W solar panel). This is measured at a high irradiance, more than is often seen in the real world so the solar panel output should be derated. In addition the solar charger buck converter efficiency varies based on the charge current and ranges between 85-93% which further derates the power from the solar panel. An estimate can be made assuming some derating for the panel and the amount of good sun hours (hours the panel can produce the derated current). Assume 4 hours of good sun at 60% panel's rated irradiance for a 35W panel and 90% efficiency for the charger as well as a constant 1.6W load.

Charge power per day = 4 * (35 * 0.6 * 0.85) = 75.6 watts
Load per day = (24 * 1.6) = 38.4 watts

This system can keep the system operating at less than 30% discharge (18 Ah battery) with good sun every other day. It will run the system for 4 days without sun keeping the battery less than 70% discharged (although it may take several days to fully recharge the battery).

A quick rule of thumb:

- Arduino-class device: 7 - 9Ah battery, 10-25W panel
- Raspberry Pi-class device: 9 - 18 Ah battery, 25-35W panel

Although the charger will limit input current from the panel to 2A, a larger panel can increase the power for the same sun over a smaller panel.

I2C Interface

The slave I2C interface is used to access 18 8- or 16-bit control registers in the charger. These control registers are split into three categories described in this section.

- Read-only 16-bit charger state values
- Read-write 16-bit charger configuration parameters
- Read-write 8-bit watchdog timeout control registers

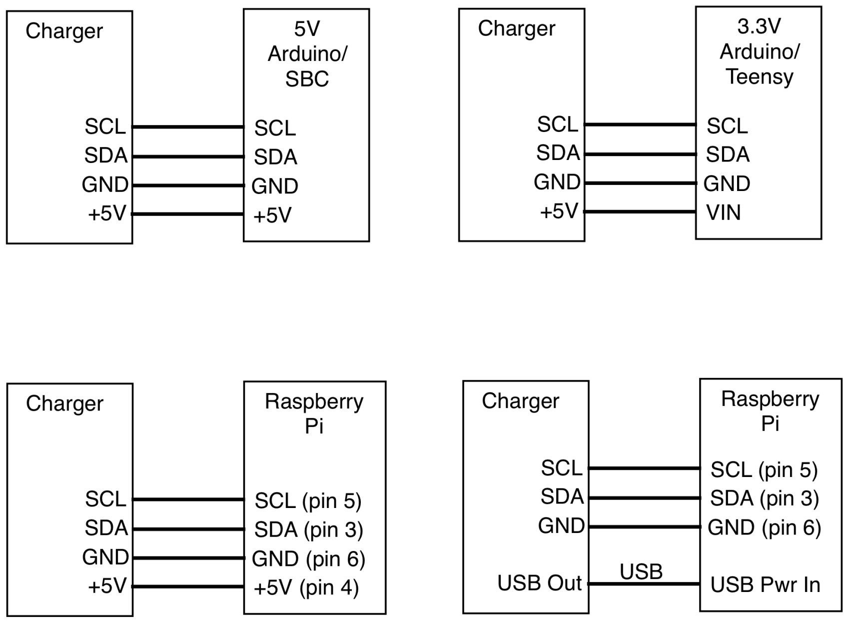
The charger has a fixed 7-bit I2C address of 0x12. It supports a maximum 100 kHz clock rate and repeated starts but does not support General Call. Registers may be read or written individually or sequentially in a burst. The 8-bit register address must written first. The high-half (bits 15:8) of 16-bit registers are presented on the bus before the low half.

Important Note regarding I2C on the Raspberry Pi

There is a hardware bug in the microprocessors used by all current Raspberry Pi computers that causes a malfunction with any I2C slave, like the charger, that can extend the I2C clock. The charger has been designed to minimize I2C clock extension but the Raspberry Pi I2C clock must be configured to 50 kHz or less in order for the hardware bug to be avoided. This can be done by adding the following line to the /boot/config.txt file.

```
dtparam=i2c_arm_baudrate=50000
```

MPPT Solar Charger i2C Connection Diagrams



Include a reference ground for I2C when using USB Cable for power.

In the examples below the **bold** fields are driven from the charger (read data).

Write Examples

Single 8-bit register:

<I2C Address+W><Register Address><Data Byte>

Single 16-bit register:

<I2C Address+W><Register Address><Data[15:8]><Data[7:0]>

Burst 16-bit registers:

<I2C Address+W><Starting Register Address><Data1[15:8><Data1[7:0> <Data2[15:8]><Data2[7:0]>…<DataN[15:8]><DataN[7:0]>

Read Examples

Single 8-bit register:

<I2C Address+W><Register Address>

<I2C Address+R>**<Data Byte>**

Single 16-bit register:

<I2C Address+W><Register Address>

<I2C Address+R>**<Data[15:8]><Data[7:0]>**

Burst 16-bit registers

<I2C Address+W><Starting Register Address>

<I2C Address+R>**<Data1[15:8]><Data1[7:0]><Data2[15:8]><Data2[7:0]> …<DataN[15:8]><DataN[7:0]>**

Register List

Register Address	Type	Size	Description
0	RO	16-bit unsigned	ID : Board ID and firmware revision

2	RO	16-bit unsigned	STATUS : Board status
4	RO	16-bit unsigned	BUCK STATUS : MPPT Buck converter status
6	RO	16-bit unsigned	VS : Solar Panel Voltage in mV
8	RO	16-bit unsigned	IS : Solar Panel Current in mA
10	RO	16-bit unsigned	VB : Battery Voltage in mV
12	RO	16-bit unsigned	IB : Battery load current in mA (current taken by load)
14	RO	16-bit signed	IC : Estimated battery charge current in mA
16	RO	16-bit signed	IT : Internal temperature sensor value in °C x 10 (25°C = 250)
18	RO	16-bit signed	ET : External temperature sensor value in °C x 10
20	RO	16-bit unsigned	VM : Current MPPT solar panel set voltage in mV
22	RO	16-bit unsigned	TH : Current, temperature compensated, battery charge voltage in mV
24	RW	16-bit unsigned	BULKV : Adjustable parameter for Bulk/Absorption state battery charge voltage in mV at 25°C. Default 14700 mV. Must be a value between 14000 - 15000.
26	RW	16-bit unsigned	FLOATV : Adjustable parameter for Float state battery charge voltage in mV at 25°C. Default 13650 mV. Must be a value between 13000 - 14000.
28	RW	16-bit unsigned	PWROFFV : Adjustable parameter for low-battery power off threshold in mV. Default 11500 mV. Must be a value between 11000 - PWRONV.
30	RW	16-bit unsigned	PWRONV : Adjustable parameter for battery recharged power restart threshold. Default 12500 mV. Must be a value between 12000 - 13000.
33	RW	8-bit unsigned	WDEN : Watchdog enable register. Write a value of 0xEA to this register to enable the watchdog function (WDCNT must also be written with a non-zero value). Write any other value, including 0, to disable the watchdog function. This register will read 0x01 if the watchdog has been enabled and 0x00 if the watchdog is disabled.
35	RW	8-bit unsigned	WDCNT : Watchdog count register. Write a value between 1 - 255 seconds to this register to set the watchdog timeout. WDEN must be enabled to start the watchdog timer counting down.
36	RW	16-bit unsigned	WDPWROFF : Watchdog power-off period. Specifies the number of seconds power will be disabled when the watchdog times out (1 - 65535). The default value is 10 seconds. The default value is loaded at power-on, and when the register is written with 0. It is also reloaded every time the watchdog times out and executes a power cycle.

<u>Charger State Values</u>

Board ID

Bits	Type	Description
15:12	RO	Board ID: This hardware version reads 1 for Board ID.
11:8	RO	Reserved: Read as 0.
7:4	RO	Firmware Version Major value.
3:0	RO	Firmware Version Minor value.

STATUS

Bits	Type	Description
15	RO - clear when read	Internal Watchdog Detected : The firmware detected an internal watchdog timeout and reset. This is separate from the Watchdog function which can be used to power cycle the user’s application. It may be set by transient conditions such as bouncing supply voltages upon connecting the battery. This bit will be cleared the first time it is read.

14	RO - clear when read	Power Watchdog Executed : The Watchdog function triggered a power-cycle of the load. This bit will be cleared the first time it is read.
13	RO	Bad Battery Status : A bad battery condition has been detected. Note that the charger power will not be enabled so the user's device must have another power supply to read this status bit set.
12	RO	External Temperature Sensor Missing : The external temperature sensor value reads less than -40°C and it is assumed to be disconnected. Compensated battery charge thresholds are being computed based on the internal temperature sensor.
11:9	RO	Reserved. Read as 0.
8	RO	Watchdog Running. Set when the Watchdog function is enabled and running. Clear when the watchdog
7	RO	Power Enable : 5V power is enabled. Note that the user's device must have another power supply to read this status bit clear.
6	RO	Alert Asserted : The ALERT output is being driven indicating that 5V power will be disabled due to a low-battery or night condition (if the jumper is bridged) within 60 seconds or is currently disabled.
5	RO	5V PWR EN Jumper : Indicates the state of the jumper. Set when the jumper is bridged, clear when the jumper is open.
4	RO	Charger Temperature Limit : Set when charging in inhibited because the temperature measured by the active temperature sensor is below -20°C or above 50°C.
3	RO	Night Detected : Set when the night condition has been detected, clear otherwise.
2:0	RO	Charge State: 0 : NIGHT - Not charging, VS < 3.5V 1 : IDLE - Not charging, 3.5V < VS < 18V 2 : VSRCV - Charger disabled for 3 seconds to let solar panel voltage float upward to open-circuit voltage prior to a SCAN. 3 : SCAN - Charger enabled and MPPT set voltage scanned through the range starting with the solar panel open-circuit voltage down to 1.5V above the current battery voltage to determine the solar panel's current maximum power point. Typically requires 4-7 seconds. 4 : BULK - Charger in Bulk Charge State 5 : ABSORPTION - Charger in Absorption Charge State 6 : FLOAT - Charger in Float Charge State

BUCK STATUS

Bits	**Type**	**Description**
15:6	RO	Charger Buck Converter PWM value (0-1023) indicating duty cycle (0-100%).
5:2	RO	Reserved. Read as 0.
1	RO	Buck Limit 2 : Set when the buck converter is limiting due to over-current or battery over-voltage limit.
0	RO	Buck Limit 1 : Set when the buck converter is limiting to keep the battery voltage at the specified threshold.

The charger measures VS, IS, VB, IB and estimates IC. It measures and averages IT and ET over an 8 second period and uses one of those values to compute TH based on the current charge state and charge threshold voltage (BULKV or FLOATV) associated with that charge state. The MPPT algorithm computes the solar panel MPPT set voltage VM.

<u>Charger Configuration Parameters</u>

BULKV and FLOATV allow the user to change the battery charge voltage thresholds to account for different lead acid battery types. These values may only be changed within the specified range. The charger will limit values outside the range.

PWROFFV and PWRONV allow the user to change the low-battery and power restart voltage thresholds respectively. The default values are industry standards but the user may wish to adjust them for specific situations.

These registers may be changed at any time and are usually written to by the user's application when it starts operating.

<u>Watchdog Function</u>

The watchdog function may be enabled to allow the charger to power-cycle the user's application if it fails to update the charger's WDCNT register periodically. This may be helpful to handle cases where the user's application has locked-up or crashed. It may also be used to disable 5V power for a specified period of 1 to 65535 seconds (18 hours, 12 minutes, 15 seconds).

Both the WDEN and WDCNT registers must be written to enable the watchdog function. The WDEN register must be written with the special value 0xEA and the WDCNT written with a non-zero value. This is a safety feature to minimize the possibility that an errant write accidently enables the watchdog function without the user application knowing this has happened. Writing any other value to WDEN or 0 to WDCNT will disable the watchdog function.

When enabled the WDCNT register is decremented once per second. When it reaches zero, Alert is asserted for 60 sends and then the 5V power is switched off for the period of time specified by the WDPWROFF register and then switched back on. The user application must write a new non-zero value to WDCNT before it counts down to zero in order to keep the watchdog function from cycling power. For example it could set WDCNT to 60 and then at an interval of less than 60 seconds update the WDNT register to 60 to prevent the watchdog function from executing.

The Power Watchdog Execute bit in the STATUS register is set when power is cycled by the watchdog function so the user application can identify cases where it was reset. The watchdog function is disabled after it cycles power and must be explicitly re-enabled by the user's application.

Watchdog Function controlling a specified power down period

The WDPWROFF register is set to 10 seconds by default, when the watchdog function is disabled via the WDEN register and each time the watchdog function times out. It may be changed to another value to allow powering down the user's application for a specified time using the watchdog function. To do this, first write the WDPWROFF register with the desired power down period, then write the WDEN and WDCNT registers to enable the watchdog timer (a small value can be used for WDCNT).

For example to power down the user's application for 8 hours (28,800 seconds):

1. Write 28800 to WDPWROFF
2. Write 10 to WDCNT
3. Write 0xEA to WDEN

The watchdog function will timeout in 10 seconds, then Alert will be asserted for 60 seconds and finally power will be shut down for 8 hours. After power is restored the watchdog function is disabled and in the default state (WDEN = 0, WDCNT = 0, WDPWROFF = 10).