By Dave Decker

"BATTERY MARVEL" 12V AUTOMOTIVE BATTERY MONITOR

This easy-to-build device alerts you well before your car, truck, boat, or motorcycle battery fails!

In this article, we're going to introduce you to the Battery Marvel — a small but powerful device designed to constantly monitor the health of common 12V lead-acid batteries found in cars, trucks, boats, motorcycles, and more. This simple project is based around a PIC microcontroller and sophisticated embedded software designed to continuously analyze your battery. The Battery Marvel gives visual and audible alerts before a battery's health becomes critical, and therefore helps prevent being caught off guard by a dead battery. It also monitors your vehicle's charging system and can identify a bad alternator, a loose fan belt, bad electrical connections, a faulty voltage regulator, plus a host of other common problems.

The Battery Marvel installs quickly and easily by connecting just two wires (power and ground). It is compatible with all 12V lead-acid batteries, including those also found in RVs, ATVs, personal watercraft, scooters, snowmobiles, and tractors. The Battery Marvel is great for vehicles in storage, as well as those you drive daily.

A single LED glows green, yellow, or red, indicating the health of your battery and electrical system at a glance. If your battery is in good condition and well charged, the Battery Marvel simply blinks green and stays quiet. If battery strength becomes marginal (yellow) or critical (red), the LED changes color and a loud audible alert is issued. The alert plays for a few minutes, and then automatically changes to an occasional reminder "chirp."

You probably already know that temperature has an impact on the performance, capacity, and service life of all batteries. The Battery Marvel continuously monitors the ambient temperature and incorporates this information into its ongoing analysis.

To support the analysis of battery condition, certain data are maintained in non-volatile Flash memory:

- A set of tables listing eight critical battery parameters vs. temperature (-40°F to 150°F).
- Historical data collected from your vehicle such as the number of engine cranks, number of engine starts, number of times the battery was disconnected, number and type of alerts issued, voltages observed, etc.
- An "abnormal" event log containing the last 64 "out of spec" events with time and temperature.
- A "normal" event log containing the last 64 "in spec" events with time and temperature.

During the first few seconds at power-up the Battery Marvel transmits the historical data and event logs optically by very rapidly blinking the red LED. In a follow-up project, we'll show you how to build an optical data reader that can capture these details and enable it to be viewed on a PC.

CAUTION: *The Battery Marvel is not compatible with high voltage (>12 volt) hybrid or electric vehicles. This device is designed to monitor common 12 volt lead-acid automotive batteries. Do not connect the Battery Marvel to high voltage (>12 volt) systems since this could be dangerous and may result in damage!*

LEAD-ACID BATTERY CONSTRUCTION

Lead-acid batteries can be broadly divided into two categories: the starting/lighting/ignition (SLI) type found in cars, trucks, and motorcycles; and the deep cycle type found in boats, golf carts, and forklifts. SLI batteries are designed to deliver maximum peak current, but they are not tolerant of being deeply discharged. In contrast, deep cycle batteries can tolerate deep discharge without damage, but they generally have a lower maximum "peak" current output than SLI batteries of similar size.

Regardless of type, every 12V lead-acid battery is constructed from six individual cells connected in series. Each cell produces about 2.108 volts at room temperature. This means that a 12V lead-acid battery actually produces about 6 x 2.108V = 12.65V at room temperature when it is fully charged. However, the cell voltage drops rapidly with temperature. At 0°F, the fully charged voltage is only 2.086V per cell and the output is around 6 x 2.086V = 12.52V. As we'll see later, a built-in temperature sensor allows the Battery Marvel to incorporate temperature into the appropriate internal calculations.

STATE OF CHARGE (SOC)

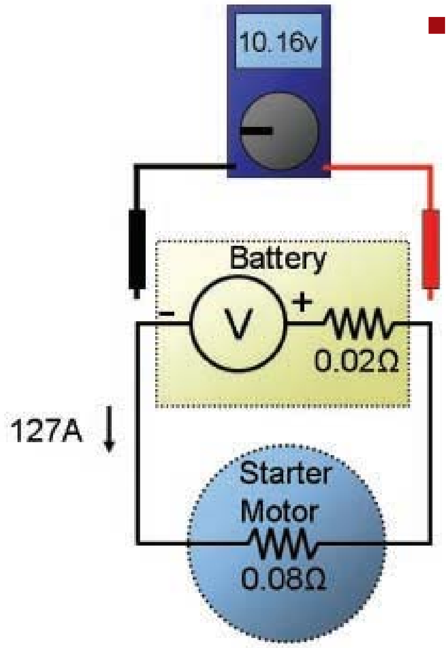
A very common measure of battery condition is "state of charge" or SOC. SOC is expressed as a percentage from 0% (fully discharged) to 100% (fully charged). The Battery Marvel continuously estimates SOC by measuring the no-load output voltage of the battery, the ambient temperature, and using a set of lookup tables in Flash memory. The Battery Marvel issues an alert if the estimated SOC drops below a minimum threshold.

Notice that a low SOC doesn't necessarily mean that a battery is bad. It might simply be low on charge because the headlights were left on or because the vehicle's charging system is not working, for example.

CAPACITY

An ideal battery has no internal resistance and is able to supply infinite current. That's a nice goal, of course, but it isn't achievable in the real world. All real batteries have some internal resistance and therefore an upper limit on the peak current they can supply.

To illustrate, let's assume that we have a 12V lead-acid battery with an internal resistance of 0.02 ohms. The peak current output of this battery is 12.65V/0.02 ohms = 633 amps. This is the current that would flow if a zero ohm load (a short circuit) was placed across the terminals. If the internal resistance of this battery increased by merely 0.01 ohms, the peak current output would drop to 12.65V/0.03 ohms = 422 amps. Thus, even a small change in a battery's internal resistance makes a big difference in the peak current output.



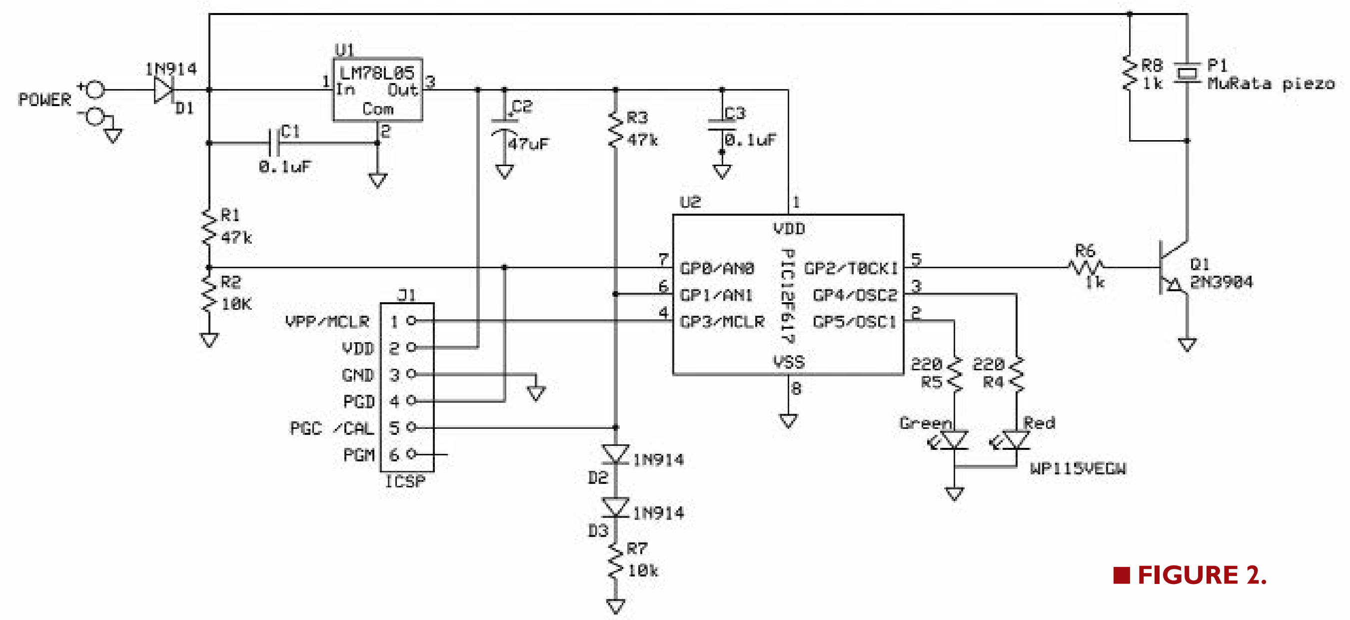
■ FIGURE 1.

CRANKING MATH

To continue with our discussion, let's assume that a particular automotive starter motor has a DC resistance of 0.08 ohms. We'd expect this starter motor to draw 12.65V / 0.08 ohms = 158 amps of peak current when it was connected to an "ideal" battery. Incidentally, it is interesting to point out here that the instantaneous current actually fluctuates rapidly, depending on the mechanical load on the starter motor at any instant — whether a winding is energized (and which one), whether a magnetic field is just starting to form, already established, or collapsing, and many other factors. The peak current and the average current through the motor are quite different, as well.

If we connected our starter motor described above to a battery with 0.02 ohms internal resistance, we'd have a 0.02 ohms + 0.08 ohms = 0.1 ohms total load which would draw 12.65V/0.1 ohms = 127 amps (peak). The minimum voltage measured across the starter motor (and also the battery posts, assuming the connecting cables have no resistance) would be 127 amps x 0.08 ohms = 10.16V. We can see that even with a fully charged, healthy battery capable of delivering 633 amps, the voltage across the battery terminals would drop to around 10.16V when the starter motor was engaged. This is illustrated in **Figure 1**.

As lead-acid batteries age, their internal resistance gradually increases. This is mainly due to a chemical build-up of hard lead sulfate crystals on the internal metal plates called "sulfation." The rate of sulfation increases as the battery's SOC drops, and it also increases with temperature. Poorly charged, hot batteries experience a



■ FIGURE 2.

much higher rate of sulfation than do fully charged cold batteries. Unfortunately, the effects of sulfation are cumulative and largely irreversible. The ever-increasing internal resistance gradually reduces the peak output of the battery, until it can no longer start the vehicle. This is how many lead-acid batteries die.

STATE OF HEALTH (SOH)

Let's assume that a certain battery has suffered some sulfation and its internal resistance has increased from 0.02 to 0.04 ohms. When the starter motor is engaged, the battery sees an effective load of 0.04 ohms + 0.08 ohms = 0.12 ohms. The current flow will be 12.65V / 0.12 ohms = 105 amps (peak). The voltage across the starter (and battery posts, assuming the cables have no resistance) drops as low as 105 amps x 0.08 ohms = 8.4V.

If a battery has good SOC and SOH, the voltage should remain above 9V when the vehicle is started at 70°F. If it doesn't, it could indicate that the battery may require some maintenance (such as adding water to one or more cells which may be low on electrolytes), or that the battery may need to be replaced.

Each time your vehicle is started, the Battery Marvel computes an SOH score (0 to 100%) based on the temperature, the SOC, and the voltage drop measured while your starter motor is engaged. A score of 100% means the battery is very healthy, i.e., there's very little drop in voltage and minimal internal resistance. A lower score is evidence of increased internal resistance and a reduced ability to deliver current. The Battery Marvel watches for deteriorating SOH and issues an alert if it becomes critical.

Complete kits are available from the *Nuts & Volts* Webstore at **http://store.nutsvolts.com**. Assembled and calibrated units are available at **www.batterymarvel.com**.

CHARGING SYSTEM

Once the engine starts, the alternator works to replenish the energy used by cranking. Modern alternators are designed to produce a varying AC voltage (linked to engine RPM) which is rectified to create an unregulated DC voltage. The unregulated DC voltage then goes to a linear voltage regulator which provides approximately 14.4V DC for powering the electrical and charging systems.

The regulated charging voltage can vary from about 13.5 to 14.8V DC, depending on the make and model of the vehicle, whether headlights or other accessories are on, SOC, and temperature. Some vehicles have a fixed-output voltage regulator while others are manually adjustable. Many newer vehicles feature a variable voltage regulator with built-in temperature compensation. This allows a higher charging voltage when the battery is cold, and a lower charging voltage when it is hot. The Battery Marvel continuously monitors your vehicle's charging system and issues an alert if any problems are detected.

SURFACE CHARGE

When the vehicle is switched off, you might expect the voltage across the battery terminals would immediately drop back to 12.65V once the engine stopped, but this is not the case. Instead, a residual "surface charge" slowly dissipates over a period of several minutes to several hours. Surface charge is due to a non-uniform concentration of ions in the electrolyte near the surface of the plates.

During charging, ions build up near the plates where the electrochemical reactions are taking place. When charging stops, the ions begin to slowly migrate away from the plates, seeking to establish a uniform concentration within the electrolyte. As the ions slowly diffuse throughout the electrolyte, the voltage gradually drops. The Battery Marvel monitors this process, and alerts you if the battery does not properly dissipate surface charge.

DESIGN AND THEORY OF OPERATION

The schematic in **Figure 2** shows the Battery Marvel is based around an eight-bit PIC12F617 (U2). The eight-pin PIC includes 2,048 14-bit words (3.5K bytes) of Flash memory, 128 bytes of RAM, and a 10-bit A/D converter. U2 is pre-programmed with software written entirely in assembly language.

Diode D1 provides reverse polarity protection in case the Battery Marvel's power and ground wires are accidentally connected "backwards." U1 — an LM78L05 linear voltage regulator — provides a stable, regulated +5V supply for U2, the temperature sensor, and the LED. This regulated supply also serves as a stable voltage reference for the U2's 10-bit A/D converter.

R1 and R2 form a simple voltage divider which scales the battery voltage down (minus the ~ 0.7V drop across D1) into a 0-5V range, suitable for the A/D converter. A typical fully charged battery voltage is 12.65V for a healthy battery which results in a scaled analog input of (12.65 – 0.7) x (10K / (10K+47K)) = 2.096V at U2's AN0 pin. J1 is a standard Microchip in-circuit serial programming (ICSP) connector, used for programming U2 "in place" on the PCB. It is not used for this project, since U2 is pre-programmed.

D2 and D3 form a very low cost ambient temperature sensor. The forward voltage drop across a silicon diode changes by roughly -2.2 mV per degree C. Here, two silicon diodes are connected in series to multiply this effect. Since our PIC has a 10-bit A/D converter with an analog input range of 0-5V, we calculate a best-case resolution of 5V/1024 = 4.8 mV. Our sensor won't win any awards for high accuracy, but it does report temperature within a few degrees and that's good enough for this application.

General-purpose NPN transistor Q1 drives P1, a piezoelectric transducer. In my initial prototype design, Q1 and R6 were not included and the piezo was instead driven directly from U2. We decided that P1 wasn't loud enough, so we added Q1 and R6 to ensure that the Battery Marvel could be heard over a vehicle's engine. The revised design generates a sound pressure level (SPL) of about 100 dB at one meter, which is extremely loud.

SOFTWARE OPERATION

The Battery Marvel's embedded software measures the battery voltage many times per second. It normalizes each voltage measurement, adjusts for ambient temperature, and takes different actions depending on the current operating state of the vehicle. See **Table 1**.

If any problems are discovered, the Battery Marvel issues an audible alert and updates the LED color as appropriate.

State	Action
Charging	Monitor vehicle charging system, charging voltage, and surface charge dissipation
Idle	Monitor SOC
Cranking	Monitor SOH

Table 1.

The software also performs many other functions such as diagnostics, calibration, optical data transmission, maintenance of historical and log data in Flash memory, and tracking the operating state of the vehicle.

CONSTRUCTION

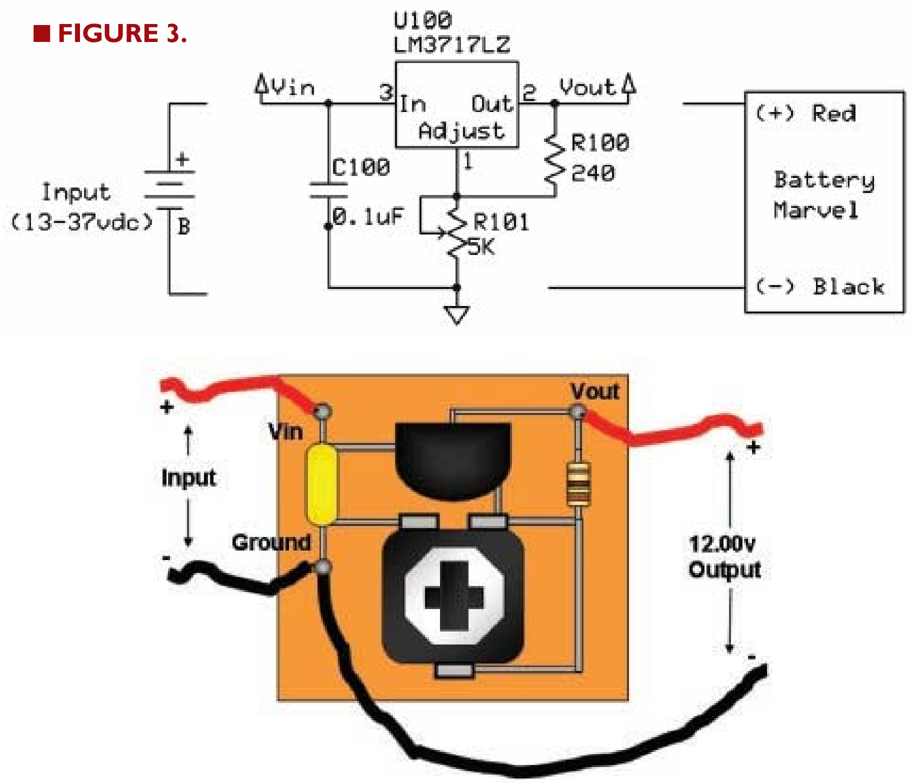
1. Begin by inserting/soldering the 1/8W resistors, R1-R8. It is important to make sure these parts lie fully flat against the PCB, as the piezo needs to mount over the top of them. The resistors are delicate — be careful not to overheat them when soldering.
2. Insert and solder diodes D1-D3. Observe the markings carefully, lining up the band on each diode with the mark on the PCB. The band on D1 goes toward the right, while the bands on D2 and D3 go toward the left. Make sure D2 and D3 lie fully flat against the PCB, since the piezo will be mounted over the top of them, as well.
3. Next, insert and solder bypass capacitors C1 and C3. These may be inserted in either direction.
4. Insert and solder U2 (the PIC12F617). The notch on the case should be toward the left.
5. Insert electrolytic capacitor C2. The negative lead goes toward the bottom of the PCB.
6. Now, insert and solder Q1, the 2N3904 NPN transistor. The flat side should be toward the left when the board is viewed from above. Q1 and U1 look almost identical, so check carefully!
7. Next, insert and solder U1, the LM78L05 voltage regulator, with the flat side toward the left.
8. Insert and solder the piezo transducer, P1. The PCB is designed so that it can be inserted in any orientation.
9. Insert LED1 with the flat side of the case toward the left. The top surface of the LED should be the same height as the piezo. If the LED is mounted too close to the PCB, the light output will be significantly reduced after it is installed in the case.
10. DO NOT power up the board yet, as there is a specific calibration procedure described in the next section.

CALIBRATION

The first time the Battery Marvel is powered up with 10V DC or more, it will attempt to calibrate itself. If you want to test it before calibrating, you can use a 9V transistor battery. It won't attempt to calibrate itself when powered by only 9V DC.

The accuracy of the calibration reference is critical to the proper operation of the Battery Marvel. If you don't

FIGURE 3.



have a 12.00V DC reference available (or a variable voltage source which can be adjusted to precisely 12.00V DC output), you may want to build one using the four extra components included with your kit. Build the circuit in **Figure 3** using the components as shown. Perfboard, breadboard, or wirewrap construction is fine.

Attach any 14-37V DC supply to the input and adjust R101 until Vout is exactly 12.00V DC. Two 9V batteries wired in series makes a good 18V input if you don't have a power supply.

Before calibrating, ensure the ambient temperature is as close to 70°F as possible. The Battery Marvel assumes during calibration that the ambient temperature is 70°F and will calibrate its temperature sensor accordingly.

Connect your completed Battery Marvel to the 12.00V DC reference source of your choice. It should make a "tick-tock" sound for 30 seconds, and the LED should alternately blink red/green. A brief alert will then be heard. This completes the calibration. The calibration data is stored in non-volatile Flash memory. You only need to calibrate once. The Battery Marvel is now ready to use.

To erase the calibration data/recalibrate, boot your kit with pins 3 and 4 of J1 (the center pins) temporarily connected. This erases the calibration data. Remove the jumper on pins 3 and 4 and calibrate as before by attaching your 12.00V DC source.

MECHANICAL

Once everything checks out, trim the stainless steel mesh and place it in the small recessed area in the case. Peel the backing from the self-adhesive Battery Marvel label and attach it to the front, fitting it carefully into the recessed area in the case.

Insert the wires through the holes in the case and solder them into place. Solder the red wire to the "+" connection on the PCB. Make sure the LED and the clear window in the label line up, then press the back of the case into place. We recommend that you wait before gluing the back — just in case. Tape the back in place temporary. Attach the Velcro to the back of the case.

INSTALLATION

A good mounting location is right on the battery itself, though you can also mount the Battery Marvel in any other convenient location, including inside your vehicle. If you decide to mount it farther from the battery, use 14 gauge or larger wire so the voltage drop is minimized.

WRAP-UP

I hope you have as much fun building and using this kit as I had creating it! Your Battery Marvel should provide you with many years of trouble-free service. **NV**

PARTS LIST

ITEM	QTY	DESCRIPTION	SUPPLIER	P/N
R1, R3	2	47K ohm resistor, 1/8W (yellow, violet, orange)	Mouser	299-47K-RC
R2, R7	2	10K ohm resistor, 1/8W (brown, black, orange)	Mouser	299-10K-RC
R4, R5	2	220 ohm resistor, 1/8W (red, red, brown)	Mouser	299-220-RC
R6, R8	2	1K ohm resistor, 1/8W (brown, black, red)	Mouser	299-1K-RC
C1, C3	2	0.1 µF bypass capacitor (10V or greater)	All Electronics	RM-104
C2	1	47 µF electrolytic capacitor (10V or greater)	Mouser	140-REA470M1ABK0511P
D1-D3	3	1N914 diode	Mouser	78-1N914
Q1	1	2N3904 NPN transistor	Mouser	610-2N3904
LED1	1	Bi-color (red/green) common cathode, T1 3 mm	Mouser	604-WP115VEGW
U1	1	LM78L05 5V voltage regulator	Mouser	512-LM7805ACZ
U2	1	Microchip PIC12F617 (programmed)	**batterymarvel.com**	PIC12F617