



## **Maxwell Active Cell Voltage Management Electronics Document # 1011130 | Revision 1.0 February 17, 2007**

Maxwell Technologies Inc. includes cell voltage management electronics in standard and custom modules for the management of cell voltage. The active voltage management circuit has undergone several generations of refinement with the current revision representing the highest reliability circuit developed to date. This document provides a detailed description of the current cell voltage management electronics and its benefits:

### **Key improvement features:**

- Elimination of module to module balancing requirements
- Improved efficiency with reduction of parasitic losses
- Improved operation over full range of temperatures
- Improved filtering and operation with noisy input power
- Increased balancing power for quicker balancing

### **Voltage Management Methodology**

The active voltage management architecture utilized in newly developed Maxwell active balancing electronics (patents pending) is a sinking topology capable of sinking current at 300-400 mA from each individual cell, whenever the specific cell voltage is in the range above or equal to 2.73 volts. The on-off trigger of the voltage management circuits have been optimized for performance in consideration of temperature and other influences. Each cell voltage is individually monitored against a nominal reference voltage. When the reference cell voltage is exceeded the voltage management circuit actively works to reduce the voltage of the cell to below the trip level. Once the cell is below the critical voltage as defined above, the voltage management circuit for that cell goes into a quiescent state with respect to balancing activity. Maintaining the cell voltage below this “trigger” level will assure the longest lifetime of the cells and, therefore, the longest lifetime of modules as well.

### Circuit Schematic

Below in Figure 1 is the circuit schematic followed with a functional description for each individual component of the topology.

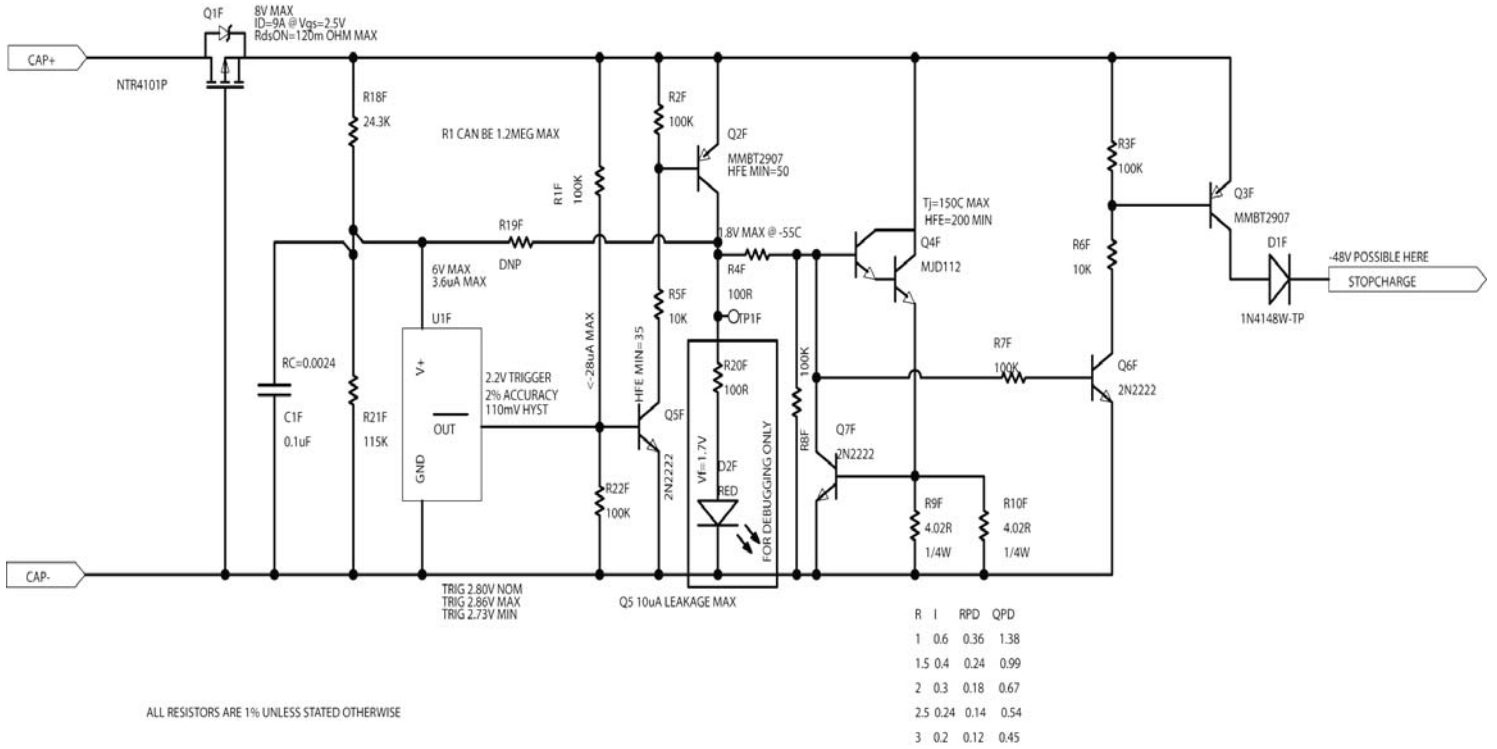


Figure 1: Voltage balancing schematic

## Circuit Functional Description

- Q1: Reverse polarity protection.
- R18, R21: Voltage divider to set the voltage management circuit discharge level.
- C1: Low pass filter with R18 to prevent oscillations and give transient suppression.
- U1: Integrated reference, comparator. Open drain output. Device pulls low until voltage threshold reached, typically 2.2V for this device. Used in conjunction with the voltage divider, sets the voltage management circuit discharge level to 2.8V. Has 100mV of hysteresis built in.
- R19: Place holder for a resistor to add additional hysteresis.
- R1: Pull up to turn on Q5 when U1 shuts off.
- Q5: First gain stage. Needed to insure operation throughout Q4's gain range.
- R5: Current limiting resistor to pull down Q2's base.
- R2: Used to prevent the base of Q2 to self-bias.
- Q2: Second gain stage.
- R4: Current limiting resistor to the base of Q4.
- R8: Used to prevent the base of Q4 to self-bias.
- Q4: Primary transistor used to dissipate the energy in the cells. Operated in constant-current mode to dissipate the most power in Q4 and not in R9/R10.
- R9, R10: Part of the current feedback circuit. Adjusted so that 0.6V across them gives the circuit the desired current. Two in parallel for better power dissipation.
- Q7: Limits the voltage on the base of Q4 to set it to constant current mode.
- R7: Current limiting resistor for the base of Q6.
- Q6: Used as an inverter to turn on Q3.
- R6: Current limiting resistor for the base of Q3.
- R3: Used to prevent the base of Q3 to self-bias.
- Q3: Sources current when the voltage management circuit is active.
- D1: All voltage management circuits are wire-ored. D1 prevents another voltage management circuit from biasing Q3.
- R20, D2: Used for debugging. LED turns on when voltage management circuit is active.

## Circuit Features & Benefits

The current topology features full reverse voltage tolerance enabling the circuit to tolerate a full reverse charge without damage to the circuit electronics or capacitors. While Maxwell does not recommend reversing the voltage on an ultracapacitor or module, the new topology continues to function correctly even in the reverse voltage condition. If an ultracapacitor module is allowed to completely self discharge, for example, it is possible that some capacitors in the module may experience a negative voltage. This negative state and subsequent recharging of the module will not cause harm to the balancing electronics.

The circuit has full temperature range compensation enabling identical performance from the circuit through the full range of operating temperatures. This feature is accomplished through a stable voltage reference subsystem for the entire temperature range ensuring accuracy of the balancing scheme while in operation. This also prevents voltage management circuit instability when the cell voltage is under fast transient conditions (discharge-charge) or if the voltage management circuit is supplied with the current directly from the capacitor.

The same topology has integrated monitoring stage which indicates an extreme stop-charge condition (when the cell exceeds maximum allowed operating voltage). Every monitoring output has an integrated analog – OR circuit. The circuit is designed to “trigger” at 2.73 volts and upon trigger will function to reduce the voltage on the cell rapidly to below the threshold of 2.70V, at which point the circuit goes quiescent again. Typical balance times are measured in minutes and the smaller the capacitance of the cell the more rapidly the voltage management circuit will reduce the voltage of that cell.

The present design has approximately one tenth the quiescent current requirements relative to the previously available balance electronics, (in these electronics, approximately 30 uA at room temperature). As a result, Maxwell’s latest modules (including the heavy duty transportation modules) featuring this circuit will exhibit an extremely low parasitic discharge contribution from the electronics. In addition, the present design tolerates wider variation in input power making it significantly more robust relative to the “dirty power” requirements with the filtering subsystem distributed across the topology.

Maxwell’s latest 16.2V and 48.6V modules have a single opto-isolated output for over voltage indication when any cell in the string approaches an over voltage condition. The nominal voltage for this over voltage condition is 2.80 (+/- 0.6 V). This signal can be monitored ensuring that the state of charge of each cell in the module is in a safe operating range. The active voltage balancing occurs prior to the threshold for over voltage signal output, so the over voltage signal is intended to be used as a stop charge signal. Charging can resume when the signal is no longer present. When the over voltage signal is triggered, failure to stop the charging will result in driving the cell to even higher voltages, damaging the cell or shortening the cell lifetime depending upon charge rate. Monitoring the over voltage signal when running the string near the maximum voltage is a good way to maximize the lifetime of the installation.

## Circuit Performance

### Self Discharge:

The present voltage management circuit's main advantage for active balancing is the minimal quiescent current draw on the module when all the cells are operating within its rated voltage. The quiescent current draw on the module is < 30μamps maximum at room temperature. Figures 2 and 3 compare self discharge behavior of a capacitor cell without balancing electronics to a module with balancing circuitry. When open circuit the module exhibits similar behavior to that of the capacitor illustrating the minimal impact of the voltage management circuit on voltage loss during self discharge of the modules. Figure 2 depicts self discharge curves of individual BCAP3000 capacitors. The rate of self discharge is then calculated below the diagram. Figure 3 illustrates the self discharge curve for two 125V modules.

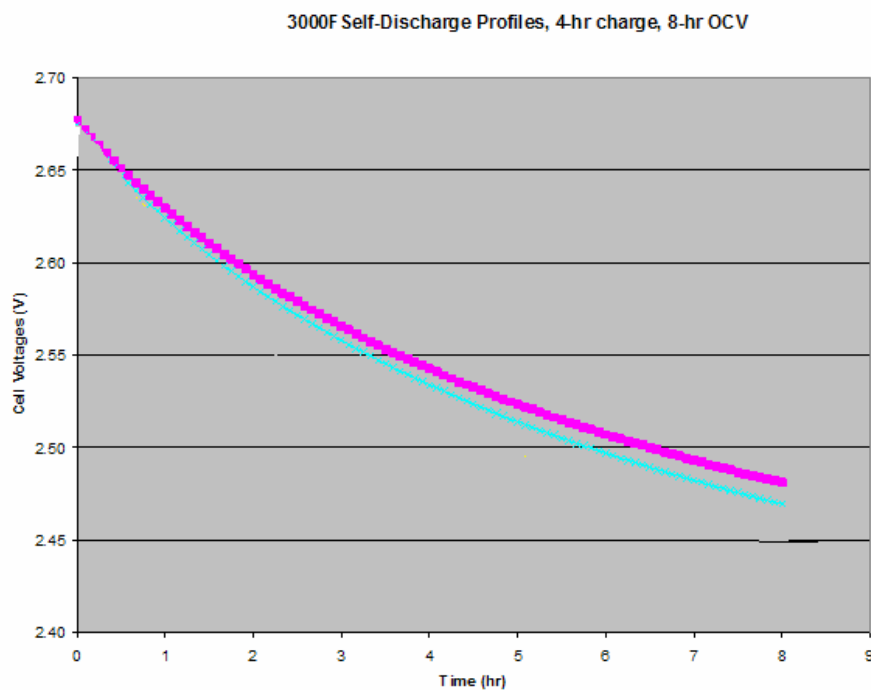


Figure 2: Self discharge behavior of BCAP3000 without balancing electronics

The voltage loss on the capacitors over an 8 hour period is calculated by the following:

$$\text{State of Charge} = \frac{V_i - V_f}{V_i} \bullet 100\%$$

From the above equation the state of charge after 8 hours is calculated to be:

$$\frac{2.67 - 2.48}{2.67} \bullet 100\% = 93\%$$

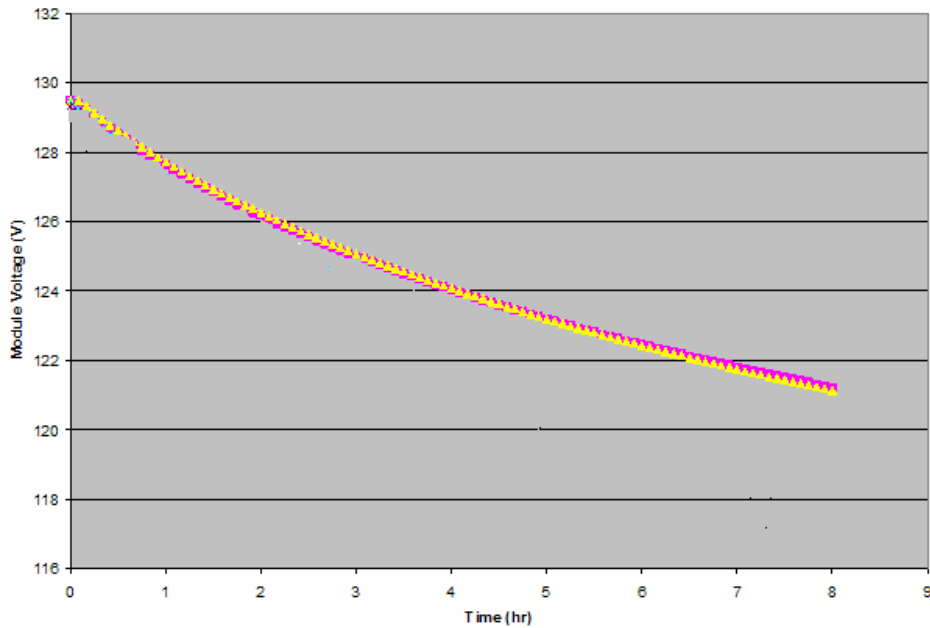
**125V Module SD Profiles, 4-hr charge at 129.6V, 8-hr OCV**

Figure 3: Self discharge of BMOD0063 P125 with balancing electronics

The voltage loss on the capacitors over an 8 hour period is calculated by the following:

$$\text{State of Charge} = \frac{V_i - V_f}{V_i} \bullet 100\%$$

From the above equation the state of charge after 8 hours is calculated to be:

$$\frac{129.6 - 121.1}{129.6} \bullet 100\% = 93\%$$

The calculations, within measurement error the graphs, indicates the remaining voltage on the 125V module is approximately the same as the remaining voltage on the individual capacitors indicating that below the trigger point the balance circuit has little to no parasitic effect on the self discharge behavior of the module.

**Cycling:**

The test data in Figure 4 illustrates a combination of voltage hold and cycle testing for a 48 V module. The module was charged to near its rated voltage and held for approximately 4 hours at an ambient of approximately 40 °C. At approximately 4 hours the module was then cycled randomly for another 4 hours. During this cycling the ambient was reduced from approximately 40 oC to 25 oC. Finally that module was discharged to approximately 1/2 rated voltage and held for approximately 14 hours. At no time during this testing did the individual capacitor voltage begin to deviate.

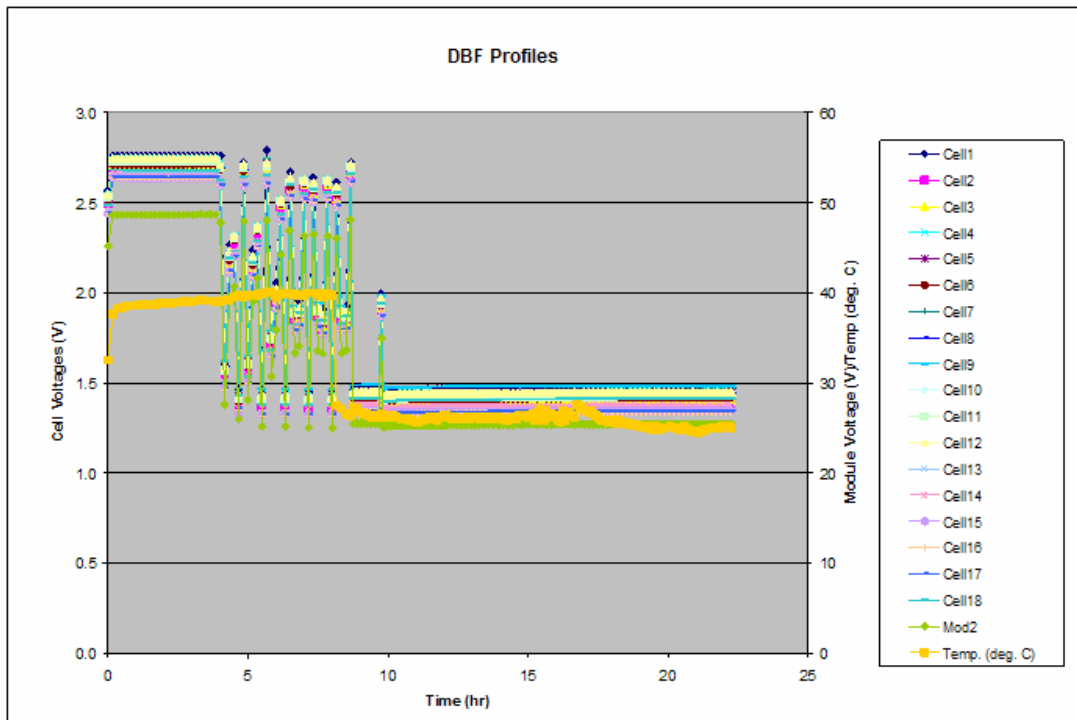


Figure 4: Cycle testing of a 48V module

## Operating Considerations

### Conditioning:

Before operation of the module, Maxwell recommends conditioning the module by charging to the maximum specified voltage and holding for approximately 1 hour. This will ensure to balance any initial charge imbalance that may have occurred during storage or shipping and handling. The same conditioning of the module can be performed to re-equilibrate the internal condition of the module at any time after commissioning as well. The present electronics do not require inter modular balancing when the modules are connected in series together in the series and, therefore, does not have inter modular balancing cables previously available.

### Reverse voltage:

As a general rule it is not a good practice to operate ultracapacitor strings in reverse voltage conditions which for short times (hours) and infrequent occurrence (Less than 100 occurrences over the lifetime of the part) is not harmful or deleterious. However, if the cell is being operated in a reverse voltage condition or being left in that condition for extended periods of time, this will result in accelerated degradation of the ultracapacitor performance and a shortening of the lifetime of the device

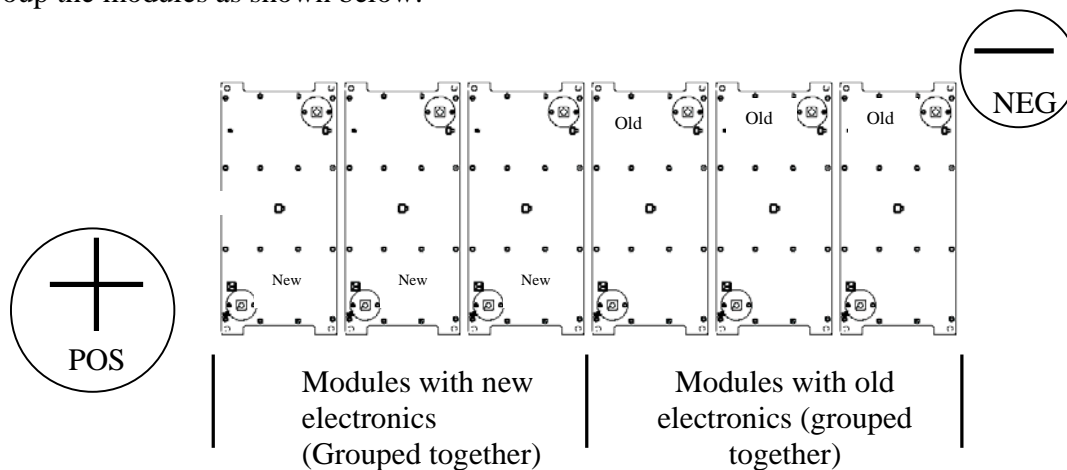
### Forward and reverse compatibility:

The present electronics is fully backward compatible with previous versions of voltage management circuits from Maxwell. The modules with the present circuit can be series connected with modules containing the previous electronics as long as the connection is made as described in the following.

When using mixed versions of modules, it is imperative the modules with the same version electronics are connected adjacent to one another and that all present version electronics are at the head of the string (nearest to the positive pole). Do **not** alternate modules of different revisions.

Example: A series string of 6 modules, 48.6V each.

**DO** group the modules as shown below:



**DO NOT** mix modules types within a string. **DO NOT** GROUP THE MODULES AS ILLUSTRATED BELOW:

