NUSolar
SC7 ELECTRICAL REPORT
WINTER 2019 (Updated Spring)

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CONTENTS

MAIN POWER WIRING

SC7's power wiring is shown below:

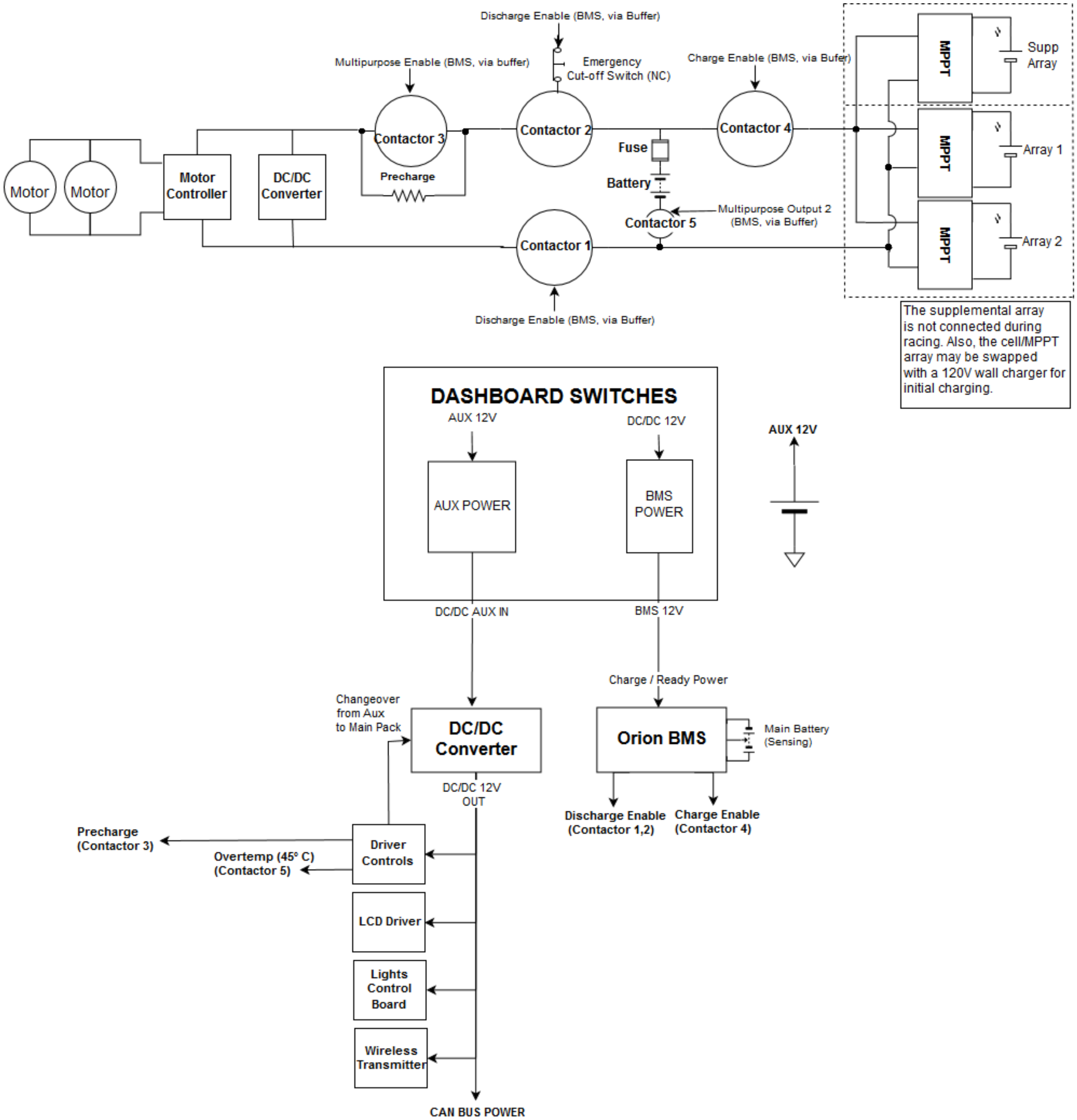

Figure 1: Power wiring for SC7 electrical system

The various operating modes are the following:

- Aux Power ON, BMS Power Off
    - All devices powered by DC/DC board receive power from the auxiliary lead-acid battery
    - CAN data is forwarded to base station (except for BMS-related packets)
- Aux Power ON, BMS Power ON
    - Discharge thresholds within range (see pg 5)
        1) Contactors 1 and 2 close, allowing current through the precharge resistor
        2) After 10 seconds, the precharge contactor closes, allowing full current to motors
    - Charge thresholds within range (see pg 5)
        1) Contactors 3 and 4 close, allowing current from the solar array OR wall charger

POWER & SPEED CALCULATIONS

BATTERY BANK CAPACITY

Each NCR18650B cell capacity is 3350 mAh, and cells in SC6 are grouped into modules (15 parallel cells per module). Since the battery pack consists of 26 modules in series, the total maximum pack capacity is thus (26 * 4.2V) * (15 * 3.35Ah) = **5487.3 Wh (fully charged)**. At minimum safe capacity, the cell voltage will be reduced to 2.8V, which corresponds to 0.75Ah remaining capacity (see Figure 2). Thus, at minimum capacity, the total pack contains (26 * 2.8V) * (15 * 0.75Ah) = **819 Wh (discharged)**. The effective capacity is thus 5487Wh-819Wh = **4668.3 Wh (effective).**

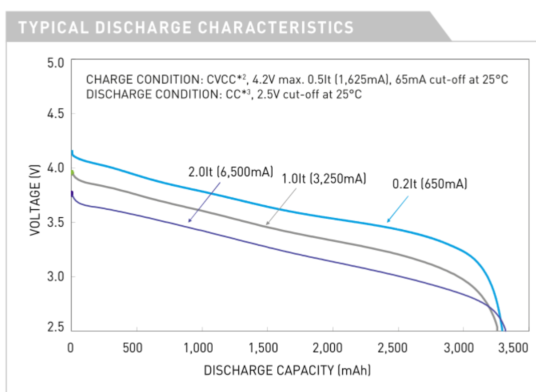

Figure 2: To stay in the linear region, cell voltage should not drop below ~2.8V. Source: Panasonic NCR18650B datasheet

SOLAR ARRAY CAPACITY

Each Maxeon Gen III Me1 solar cell provides 3.72W. The total array (not including supplementary) consists of 256 cells; thus, the total output is 952 W. The MPPT peak efficiency is 97.5%; thus, the best-case output in sunny conditions while racing is **928W**.

When using the supplementary array, the total cell count is 384. Thus, the best-case output while stationary charging in sunny conditions is **1392.768W**.

Motor Power Draw

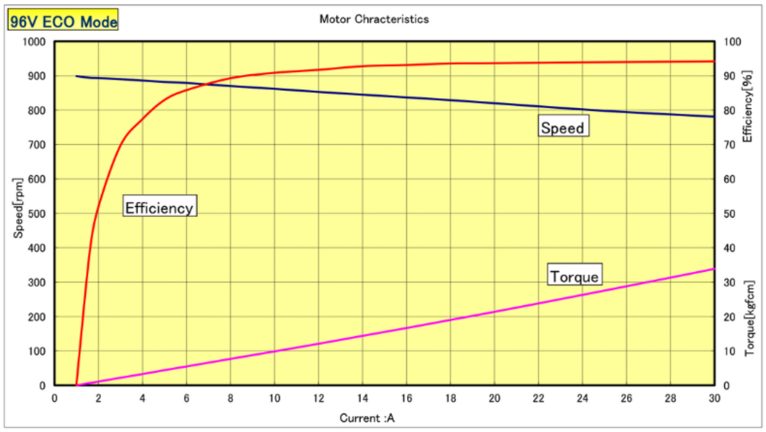

Figure 3: Mitsuba motor speed, torque, and efficiency as a function of current draw. Note that the scale for torque is incorrect—it should read units of Nm, not kgfcm. Source: Mitsuba M2096 datasheet

Assuming the car mass is 360kg, the combined torque from two motors is 65Nm (see Figure 3), and the wheel radius is 0.2286m, we may calculate the acceleration time from 0-45mph:

$$F = \frac{\tau}{\mathrm{r}} = \frac{65\ \mathrm{Nm}}{0.2286\ \mathrm{m}} = 284.3\ \mathrm{N}$$

$$a = \frac{F}{m} = \frac{284.3\ \mathrm{N}}{360\ \mathrm{kg}} = 0.79\ \mathrm{m/s^2}$$

$$t_{0-45mph} = \frac{20.1\frac{m}{s} - 0\frac{m}{s}}{0.79\ m/s^2} = \mathbf{25.44\ sec}$$

When the car is at constant speed, however, the motors must only supply enough torque to overcome the drag force. Assuming the drag force at 45mph

$$\tau_{required} = \mathrm{r\ x\ F} = (0.2286\ \mathrm{m})(175\ \mathrm{N}) = \ 40\ \mathrm{Nm}$$

Thus, 20 Nm of torque from each motor must be supplied, requiring about 18 A per motor (see Figure 3). This requires an overall power of 2*(18A)*(96V)=**3456 W.**

Discharge Time (Racing)

$$P_{net} = P_{in} - P_{out} = 928W - 3456\mathrm{W} = \text{-2528W}$$

$$t_{toEmpty} = \frac{4668.3\ \mathrm{Wh}}{2528\ \mathrm{W}} = \mathbf{1.85\ hr}$$

Assuming continuous racing at 45mph (no acceleration, main solar array only), the battery bank will be emptied to 2.8V after 1.85 hours.

Charge Time (Stationary)

Assume the battery pack is emptied to 2.8V, and the car is charging with the main array and supplementary array. Then it will take $\frac{4668.3\ \text{Wh}}{1392.768\ \text{W}} = \mathbf{3.35\ hours}$ to regain full charge.

Battery Management System

Due to faulty hardware and outdated software on the Tritium BMS used in SC6, the team purchased a new BMS system from Ewert Energy Systems. This system was chosen to satisfy the following requirements:

1) **Cell Measurement**
    a. Compatible with 3.6V – 4.2V cell chemistry
    b. Individually monitor voltage on at least 26 cells/modules in series
    c. Centralized rather than board-per-cell topology
    d. Includes current-measurement for at least 100A
2) **I/O**
    a. Drives 12V contactors up to 0.13A continuously and 3.8A surge (KILOVAC EV200 contactors)
    b. Includes output to enable DC/DC converter
    c. Supports pre-charge
    d. CAN support
3) **Software**
    a. Compatible with Windows 7+
    b. Customizable CAN commands

The Orion BMS 2 (distributed by Ewert Energy Systems) satisfies all criteria under (1) and (3). However, additional circuitry must be designed to facilitate I/O functions (a) and (c)—one such solution will be proposed in this section.

CELL MEASUREMENT

The Orion BMS 2 is custom-ordered for the size of the battery bank. Available sizes are multiples of 12, so the 36 cell model is necessary to support our 26-module battery bank. For convenience and reliability, we purchased a factory-assembled voltage-tap cable for connection between the cells and the BMS. The only significant complication involved in this process is the fact that **the 10 unused cell taps must be wired together per Orion's online wiring chart generator:**

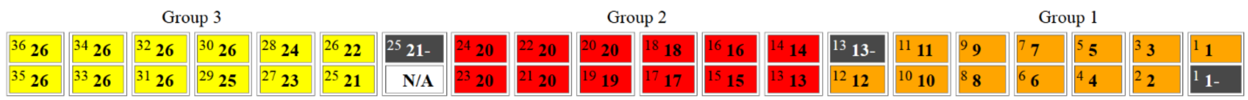

Figure 4: Wiring diagram for cell tap connector (https://www.orionbms.com/tools/wiring.php). Each wire connects to the positive terminal of the numbered cell, except for "1-", "13-", and "21-", which connect to the negative terminal of the respective cells. Note how all but 3 of the 12 wires in Group 3 are connected to the same cell.

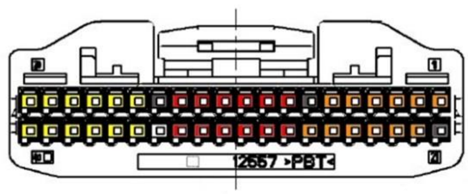

Figure 5: Cell tap connector (physical view); colors correspond to Figure 4

Sold separately with the Orion BMS 2 is a hall-effect current transformer, which measures the total battery pack current. A current sensor with the proper maximum rating must be selected; for SC7, I chose the 200A model (base model), as the net current should never exceed 80A.

The Orion BMS 2 does include temperature sensors; however, only 8 are included with the base model (26 modules need to be monitored). For this reason, I will continue using our external daisy-chainable DS18B20 digital temperature sensor system (tested on SC6).

I/O

While the Orion BMS does include contactor-drive outputs, the Wiring Manual states that only two contactors may be driven simultaneously due to power limitations. To allow for the use of more than two contactors, I designed a relay buffer board to interface between the BMS outputs and all five contactors. Relays were chosen instead of MOSFETs for simplicity and to avoid potential noise issues from the PWM economizer circuitry inside the EV200 contactors.

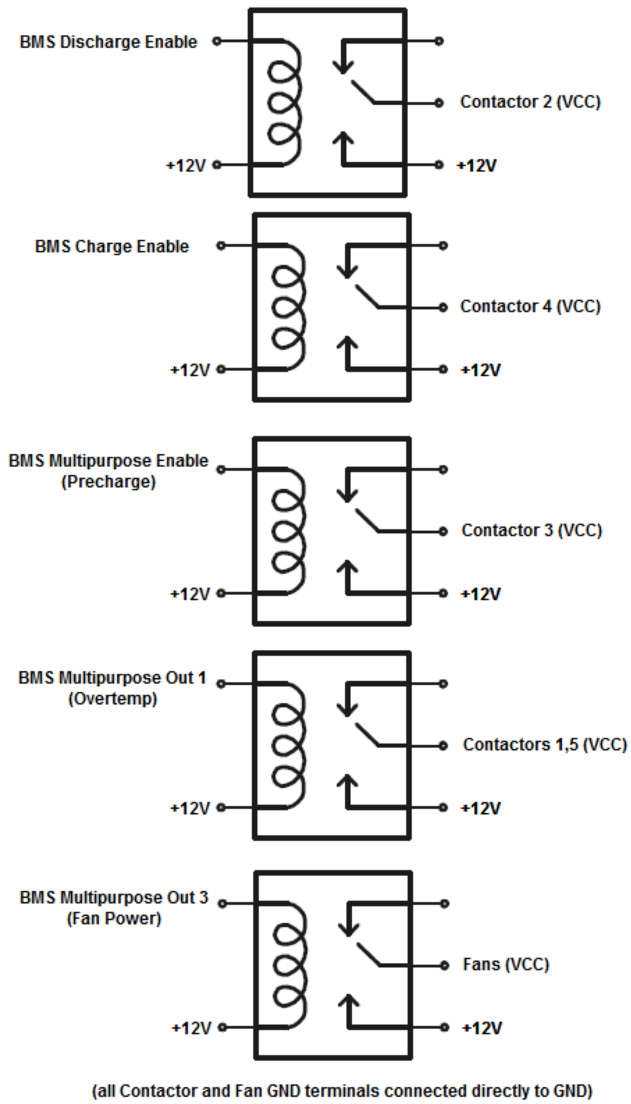

Figure 6: External buffer circuitry to allow control of all 5 contactors, and fans

T9AP1D52-12 normally-open relays are suitable for this application for the following reasons:

- Relay coil draws only 83 mA (BMS outputs rated for 500 mA)
- Rated output is 15A (EV200 contactors draw only 4A max, during surge)
- Inexpensive ($3.40 / relay)

SOFTWARE

The following needs be defined in the BMS software:

- Thresholds
  - Charge Thresholds (if any unmet, disable Charge Enable contactor)
    - Over-current limit (total) = **24A** (1.625 A per cell * 15 cells in parallel)
    - Over-temp limit (per cell) = **45 degrees C**
    - Over-voltage limit (per cell) = **4.18V**
    - Under-voltage limit (per cell) = **2.8V**
  - Discharge Thresholds (if any unmet, disable Discharge Enable contactor)
    - Over-current limit (total) = **75A** (max reasonable current drawn by motors)
    - Over-temp limit (per cell) = **60 degrees C**
    - Over-voltage limit (per cell) = **4.18V**
    - Under-voltage limit (per cell) = **2.8V**
  - Cell Balance Conditions (if any unmet, stop balancing pack)
    - Balance cells **above 3.3V**
    - Stop balancing once all cells within **0.005V**
    - Do not balance individual cells below **3.2V**
- CAN Packets
  - Outgoing packet containing all cell voltages and total current
  - Incoming packet containing a Boolean **WITHIN TEMP RANGE/NOT WITHIN TEMP RANGE** signal from Driver Controls

All such parameters may be set in the Orion BMS 2 Control Application. Screenshots are provided below as a guide to future members:

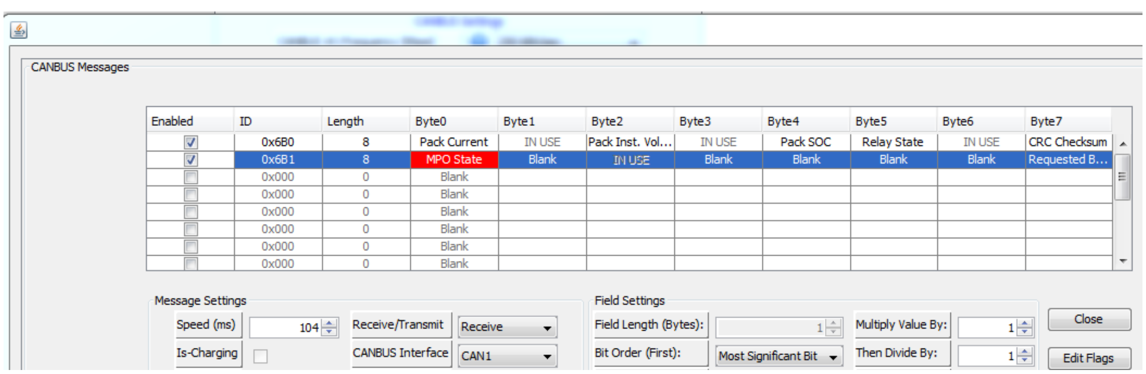

Figure 7: Custom CAN packets and associated functions may be added in the BMS software under "CANBUS Settings". Packet 0x6B1 will be received from the Driver Controls board, indicating that the temperature sensors are within range (or not). This Boolean value determines the state of Contactors 1 and 5 (see Main Power Wiring section).

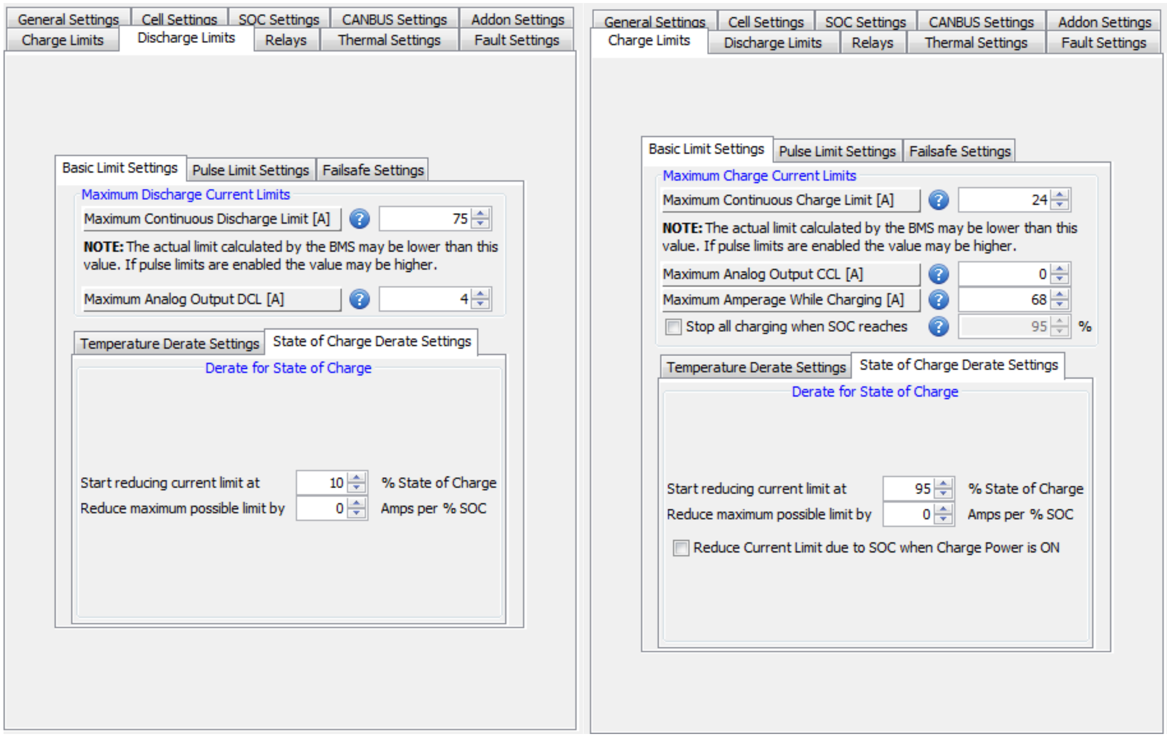

Figure 8: The discharge and charge currents may be defined as shown. Note that "reduce maximum possible limit" should be set to zero unless this feature is factored into the design.

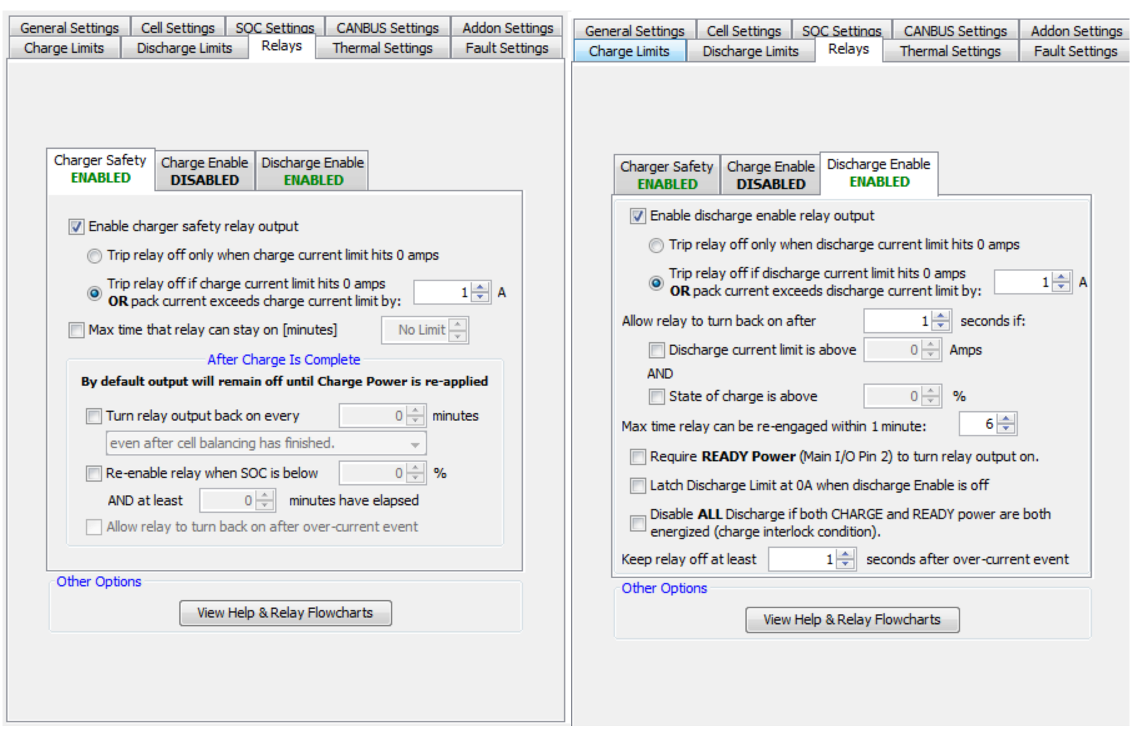

Figure 9: The enforcement of the current limits is defined here. "Trip relay off if current limits hits 0 amps" refers to the de-rating feature described in Figure 8 and is not being used in SC7.

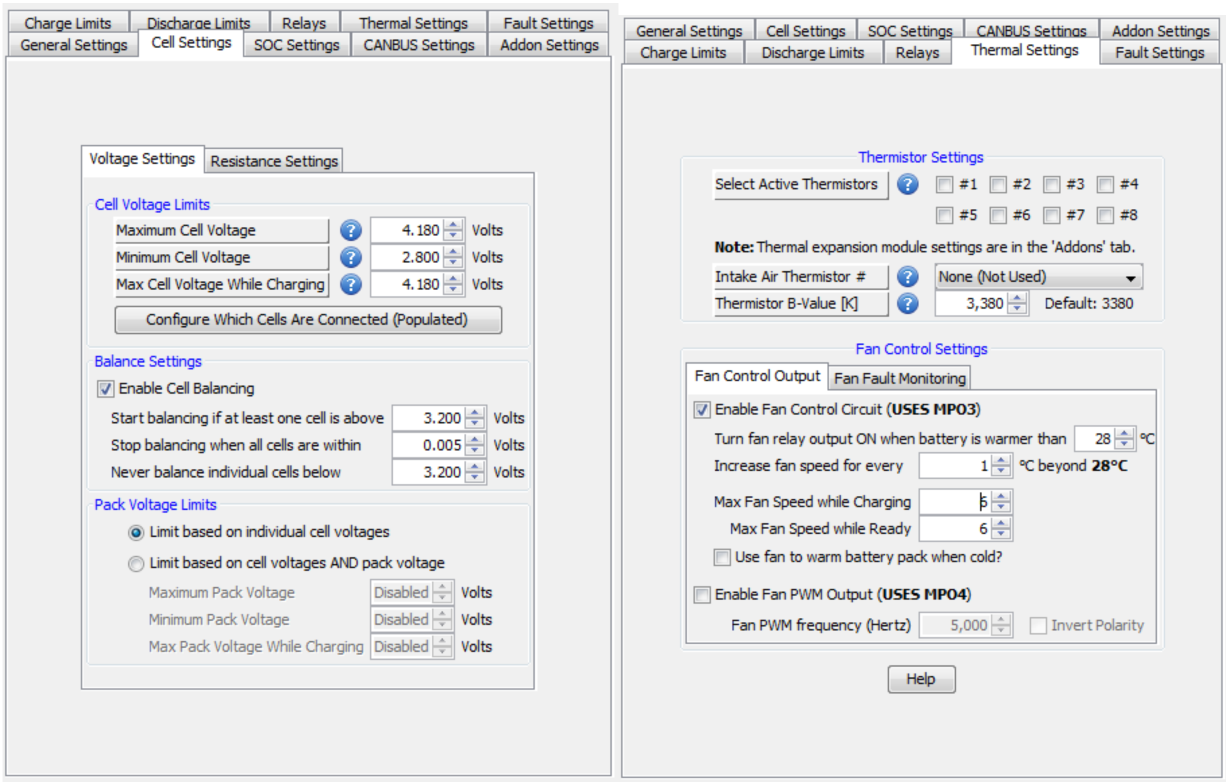

Figure 10: The conditions for cell-balancing and fan drive may be defined here.

BATTERY BOX LAYOUT

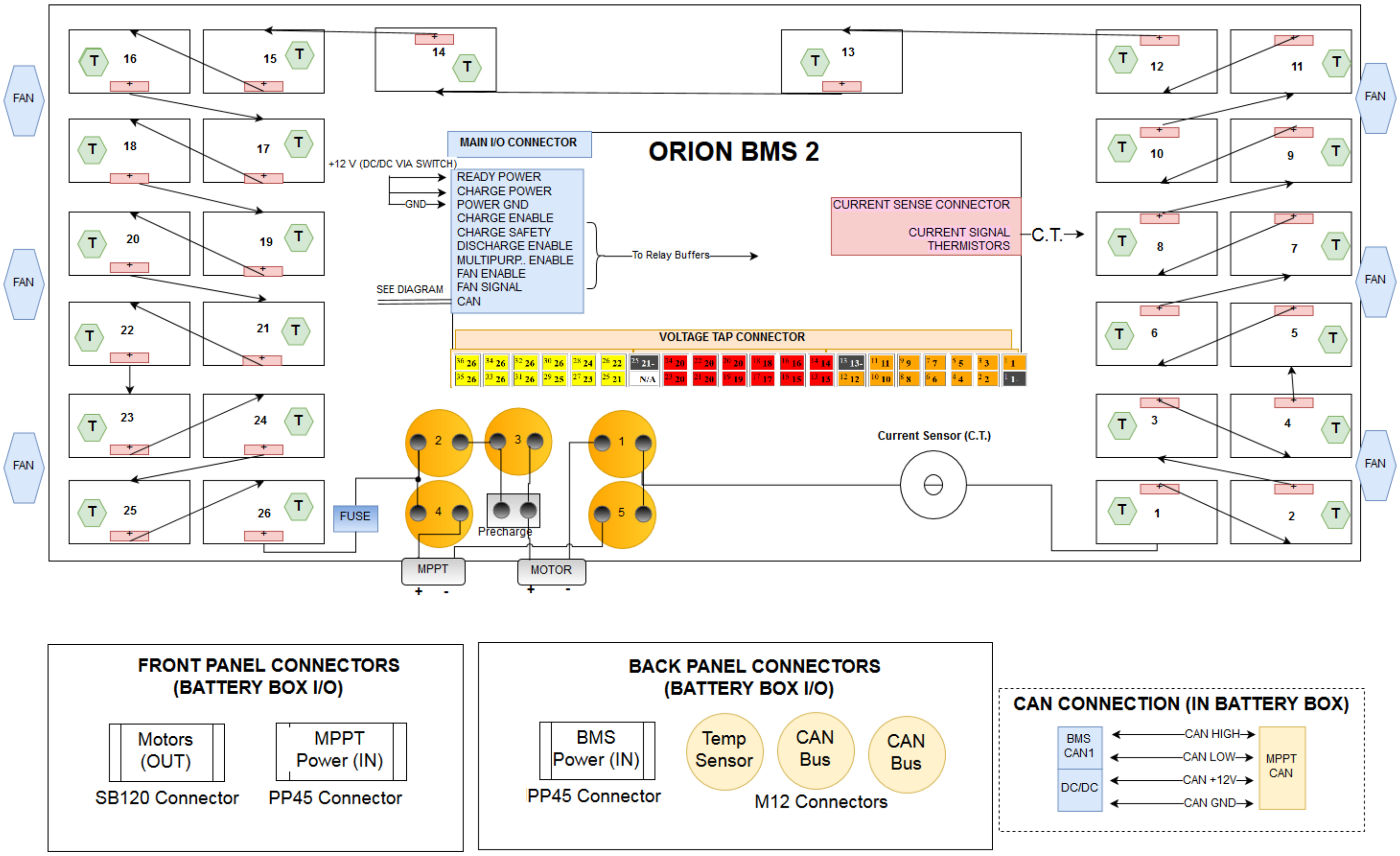

Figure 11: Physical layout of battery box. The wiring direction in the battery box changes to make room for a horizontal reinforcement rib across the length of the battery box. Each “T” hexagon represents a DS18B20 temperature sensor.

TELEMETRY

The most recent implementation of telemetry hardware was tested on SC6. The team used a 125mW Digi Xpress Ethernet Bridge and external antenna to transmit CAN packets wirelessly to the base-station. This setup had issues with signal strength when the car was on the far end of the track; hence, a new 1W transceiver (Digi Xbee ® SX RF Modem) was chosen, using the same basic system layout (see Figure 12). This should improve the range over last year by a factor of 4 (since power is distributed among the surface of a sphere of area $4\pi r^2$, a change in power of factor 8 should change radius by factor 4).

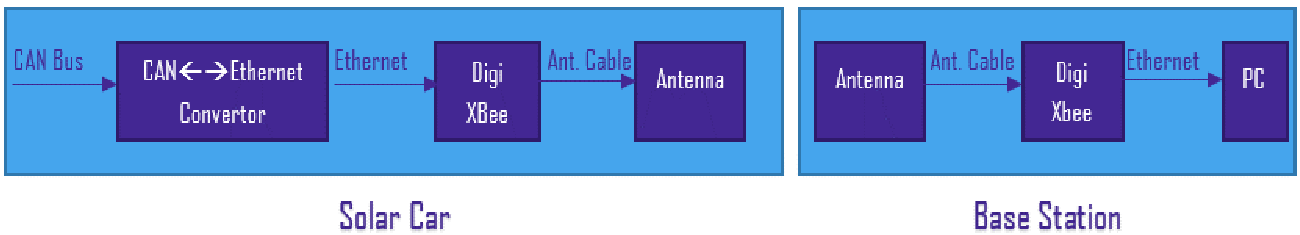

Figure 12: Telemetry system for SC7

An antenna was selected to match the Xbee's SMA connector and center frequency (915 MHz). An additional consideration is that the antenna should exhibit an omnidirectional gain; i.e., not focused in any particular direction. The Linx ANT-916-ID satisfies all the criteria.

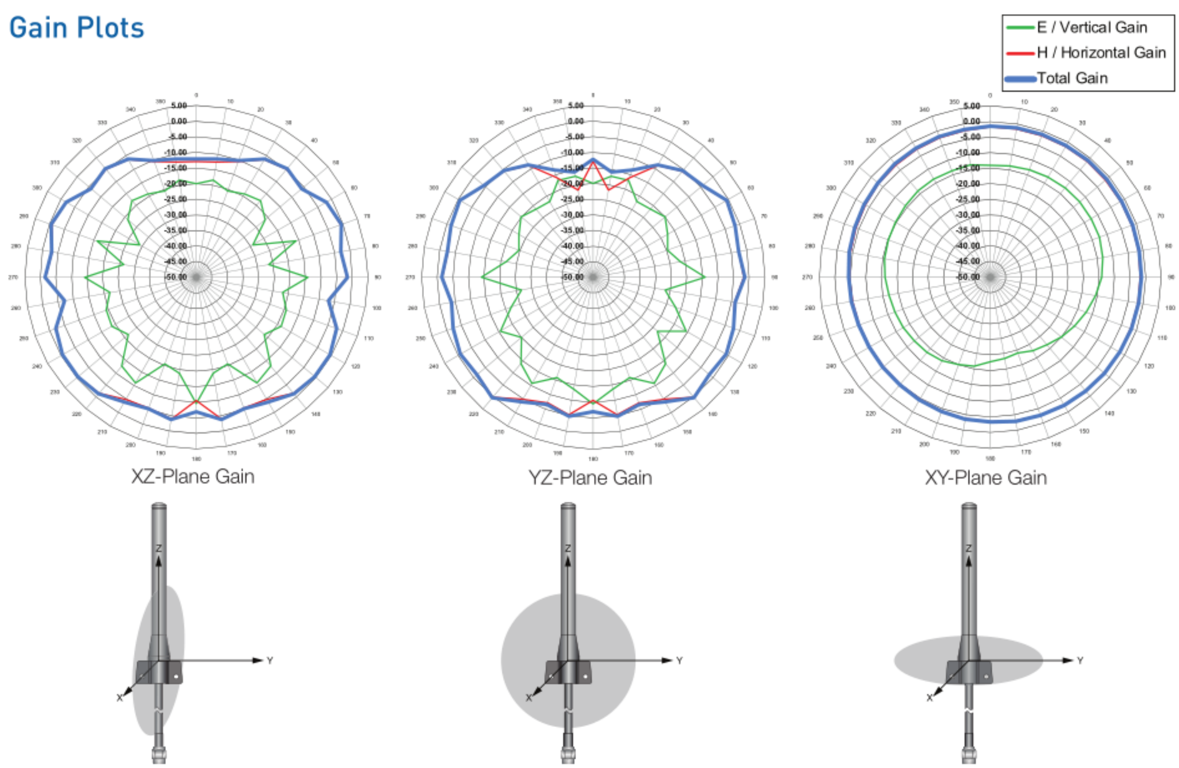

Figure 13: The ANT-916-ID gain plot shows that it is fairly omnidirectional

Logic Power

DCDC Outs

BMS

Logic – 2 W @ 12V = 0.167 A

Relay board -- 83 mA per relay * 5 relays = 0.415 A

Contactors (steady state) -- 130mA per contactor * 5 = 0.65 A

Contactors (surge) – 3800 mA per contactor * 5 = 19 A

Fans – 1.5A per fan * 6 = 9 A

Total (steady) = 10.2A

12A fuse (slow-blow)

CAN Bus

MPPT 450 mA

Temp 80mA

LCD 200 mA

Arduinos 50 mA

Total = 0.78 A

1A fuse

Light Board

Turn signal lights = 0.05A * 8 = 0.4A

Headlamps = 0.1 * 2 = 0.2 A

Strobe lamp = assume 0.2A

Horn = 1.5A

Total = 2.3 A

2.5A fuse