

NUSolar

SC7 ELECTRICAL REPORT

WINTER 2019 (Updated Spring)

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MAIN POWER WIRING

SC7's power wiring is shown below:

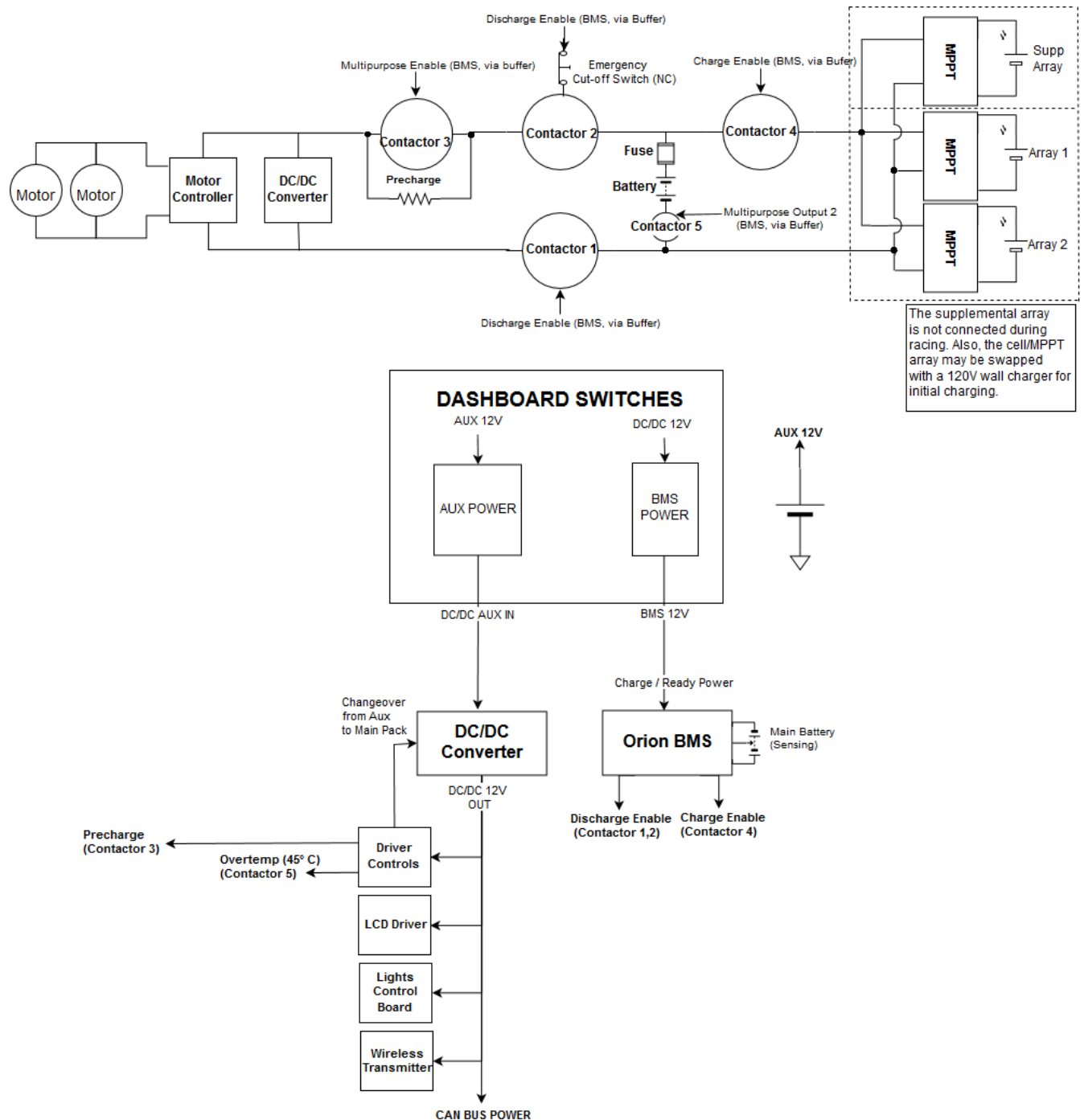


Figure 1: Power wiring for SC7 electrical system

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 $(26 * 4.2V) * (15 * 3.35Ah) = \mathbf{5487.3\ Wh\ (fully\ charged)}$. 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 $(26 * 2.8V) * (15 * 0.75Ah) = \mathbf{819\ Wh\ (discharged)}$. The effective capacity is thus $5487Wh - 819Wh = \mathbf{4668.3\ Wh\ (effective)}$.

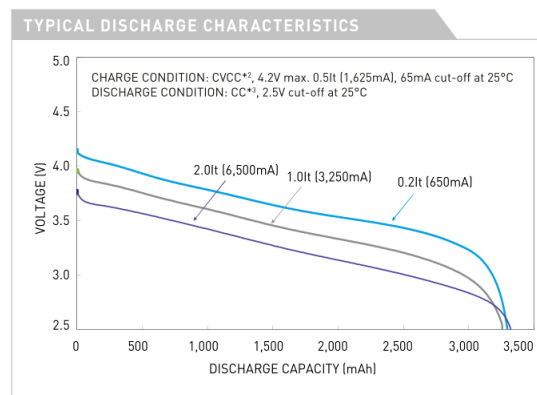


Figure 2: To stay in the linear region, cell voltage should not drop below ~2.8V. Source: Panasonic NCR18650B datasheet

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

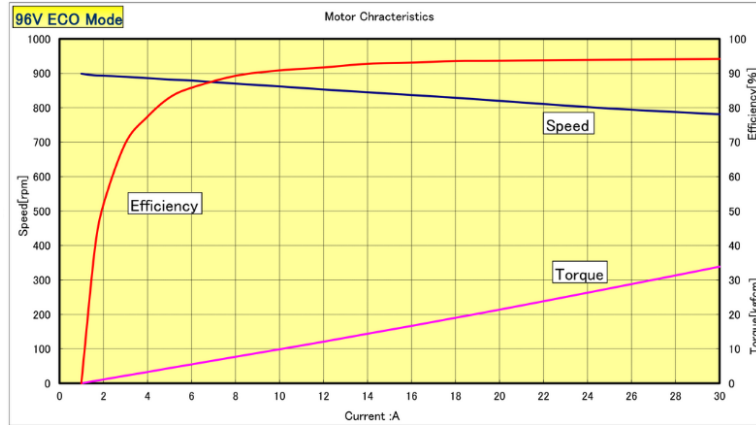


Figure 3: Mitsubishi motor speed, torque, and efficiency as a function of current draw. Note that the scale for torque is incorrect—it should read units of Nm, not kgfcm. Source: Mitsubishi M2096 datasheet

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:

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

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

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

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

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

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 $2 \times (18\text{A}) \times (96\text{V}) = \mathbf{3456 \text{ W}}$.

DISCHARGE TIME (RACING)

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

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

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 $\frac{4668.3 \text{ Wh}}{1392.768 \text{ W}} = \mathbf{3.35 \text{ hours}}$ 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.

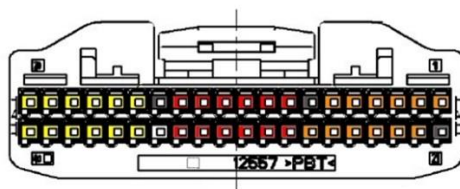


Figure 5: Cell tap connector (physical view); colors correspond to Figure 4

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.

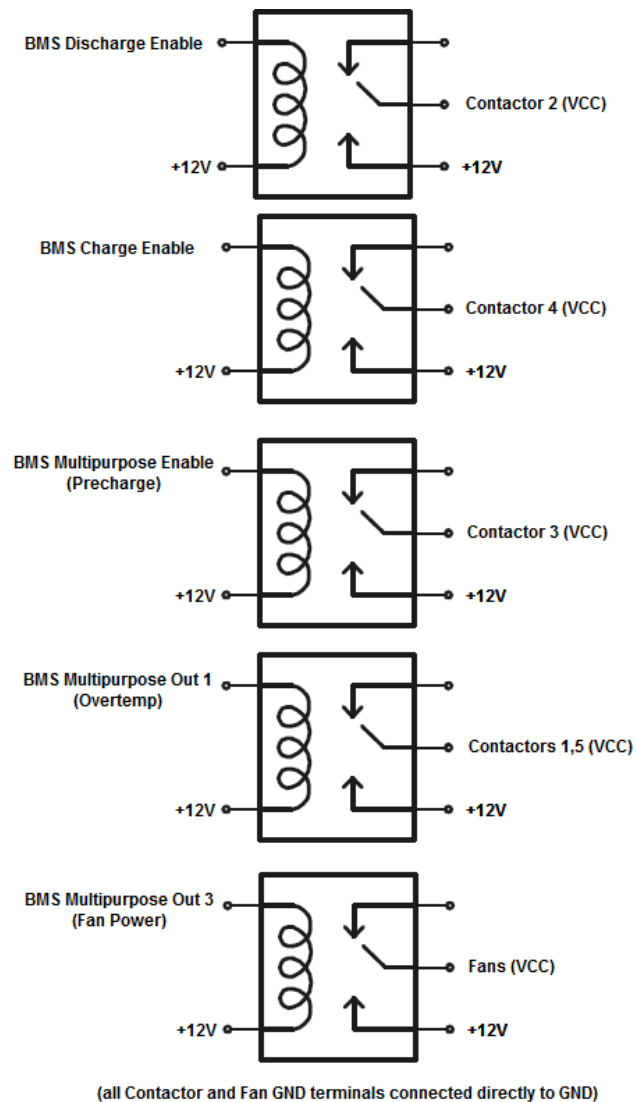


Figure 6: External buffer circuitry to allow control of all 5 contactors, and fans

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:

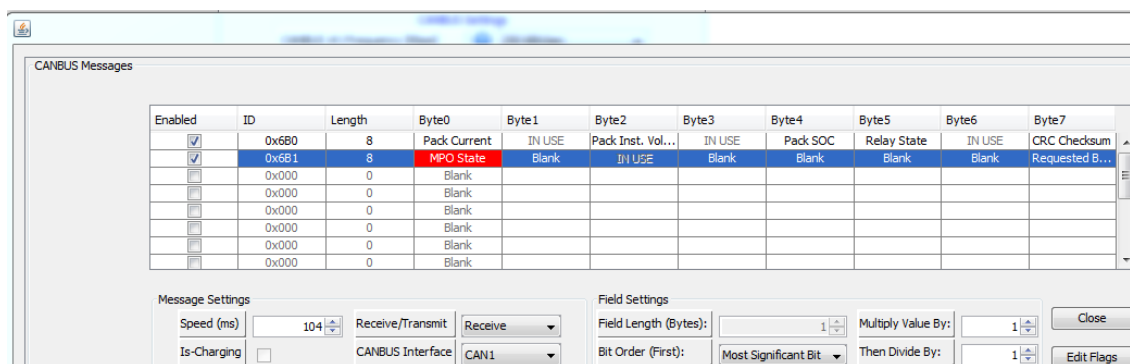


Figure 7: Custom CAN packets and associated functions may be added in the BMS software under "CANBUS Settings". Packet 0x6B1 will be received from the Driver Controls board, indicating that the temperature sensors are within range (or not). This Boolean value determines the state of Contactors 1 and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

General Settings
Cell Settings
SOC Settings
CANBUS Settings
Addon Settings
Charge Limits
Discharge Limits
Relays
Thermal Settings
Fault Settings

Basic Limit Settings
Pulse Limit Settings
Failsafe Settings

Maximum Discharge Current Limits
Maximum Continuous Discharge Limit [A] ? 75
NOTE: The actual limit calculated by the BMS may be lower than this value. If pulse limits are enabled the value may be higher.
Maximum Analog Output DCL [A] ? 4
Temperature Derate Settings
State of Charge Derate Settings
Derate for State of Charge
Start reducing current limit at 10 % State of Charge
Reduce maximum possible limit by 0 Amps per % SOC

General Settings
Cell Settings
SOC Settings
CANBUS Settings
Addon Settings
Charge Limits
Discharge Limits
Relays
Thermal Settings
Fault Settings

Basic Limit Settings
Pulse Limit Settings
Failsafe Settings

Maximum Charge Current Limits
Maximum Continuous Charge Limit [A] ? 24
NOTE: The actual limit calculated by the BMS may be lower than this value. If pulse limits are enabled the value may be higher.
Maximum Analog Output CCL [A] ? 0
Maximum Amperage While Charging [A] ? 68
Stop all charging when SOC reaches 95 %
Temperature Derate Settings
State of Charge Derate Settings
Derate for State of Charge
Start reducing current limit at 95 % State of Charge
Reduce maximum possible limit by 0 Amps per % SOC
Reduce Current Limit due to SOC when Charge Power is ON

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.

General Settings
Cell Settings
SOC Settings
CANBUS Settings
Addon Settings
Charge Limits
Discharge Limits
Relays
Thermal Settings
Fault Settings

Charger Safety
Charge Enable
Discharge Enable
ENABLED
DISABLED
ENABLED

Enable charger safety relay output
Trip relay off only when charge current limit hits 0 amps
Trip relay off if charge current limit hits 0 amps OR pack current exceeds charge current limit by: 1 A
Max time that relay can stay on [minutes] No Limit
After Charge Is Complete
By default output will remain off until Charge Power is re-applied
Turn relay output back on every 0 minutes even after cell balancing has finished.
Re-enable relay when SOC is below 0 % AND at least 0 minutes have elapsed
Allow relay to turn back on after over-current event
Other Options
View Help & Relay Flowcharts

General Settings
Cell Settings
SOC Settings
CANBUS Settings
Addon Settings
Charge Limits
Discharge Limits
Relays
Thermal Settings
Fault Settings

Charger Safety
Charge Enable
Discharge Enable
ENABLED
DISABLED
ENABLED

Enable discharge enable relay output
Trip relay off only when discharge current limit hits 0 amps
Trip relay off if discharge current limit hits 0 amps OR pack current exceeds discharge current limit by: 1 A
Allow relay to turn back on after 1 seconds if:
Discharge current limit is above 0 Amps
AND
State of charge is above 0 %
Max time relay can be re-engaged within 1 minute: 6
Require READY Power (Main I/O Pin 2) to turn relay output on.
Latch Discharge Limit at 0A when discharge Enable is off
Disable ALL Discharge if both CHARGE and READY power are both energized (charge interlock condition).
Keep relay off at least 1 seconds after over-current event
Other Options
View Help & Relay Flowcharts

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.

Charge Limits

Discharge Limits

Relays

Thermal Settings

Fault Settings

General Settings

Cell Settings

SOC Settings

CANBUS Settings

Addon Settings

Voltage Settings

Resistance Settings

Cell Voltage Limits

Maximum Cell Voltage

4.180

Volts

Minimum Cell Voltage

2.800

Volts

Max Cell Voltage While Charging

4.180

Volts

Configure Which Cells Are Connected (Populated)

Balance Settings

☒ Enable Cell Balancing

Start balancing if at least one cell is above

3.200

Volts

Stop balancing when all cells are within

0.005

Volts

Never balance individual cells below

3.200

Volts

Pack Voltage Limits

☒ Limit based on individual cell voltages

☐ Limit based on cell voltages AND pack voltage

Maximum Pack Voltage

Disabled

Volts

Minimum Pack Voltage

Disabled

Volts

Max Pack Voltage While Charging

Disabled

Volts

General Settings

Cell Settings

SOC Settings

CANBUS Settings

Addon Settings

Charge Limits

Discharge Limits

Relays

Thermal Settings

Fault Settings

Thermistor Settings

Select Active Thermistors

☐ #1
☐ #2
☐ #3
☐ #4
☐ #5
☐ #6
☐ #7
☐ #8

Note: Thermal expansion module settings are in the 'Addons' tab.

Intake Air Thermistor #

None (Not Used)

Thermistor B-Value [K]

3,380

Default: 3380

Fan Control Settings

Fan Control Output

Fan Fault Monitoring

☒ Enable Fan Control Circuit (USES MP03)

Turn fan relay output ON when battery is warmer than

28

°C

Increase fan speed for every

1

°C beyond 28°C

Max Fan Speed while Charging

5

Max Fan Speed while Ready

6

☐ Use fan to warm battery pack when cold?

☐ Enable Fan PWM Output (USES MP04)

Fan PWM frequency (Hertz)

5,000

☐ Invert Polarity

Help

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

10

BATTERY BOX LAYOUT

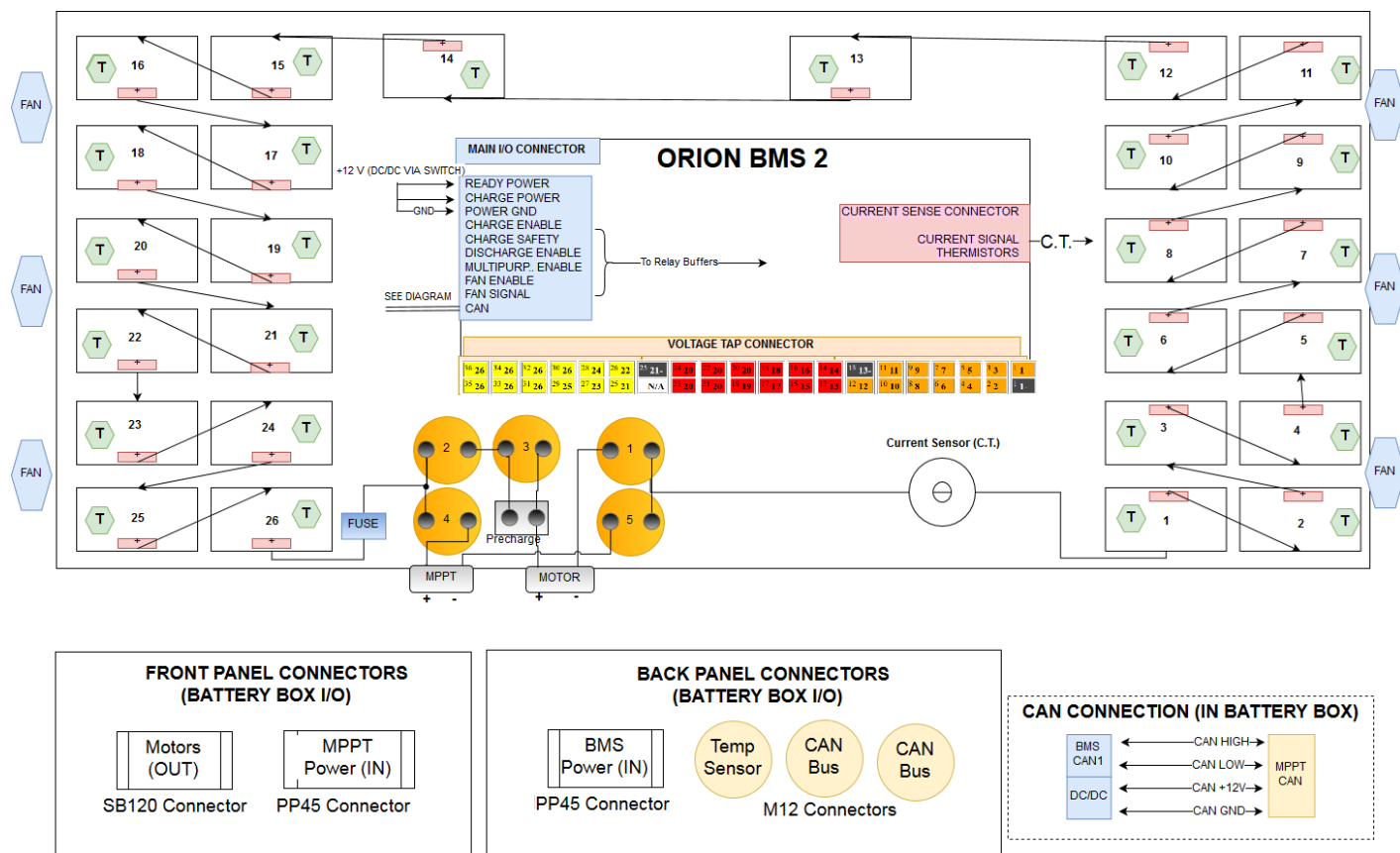


Figure 11: Physical layout of battery box. The wiring direction in the battery box changes to make room for a horizontal reinforcement rib across the length of the battery box. Each "T" hexagon represents a DS18B20 temperature sensor.

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).

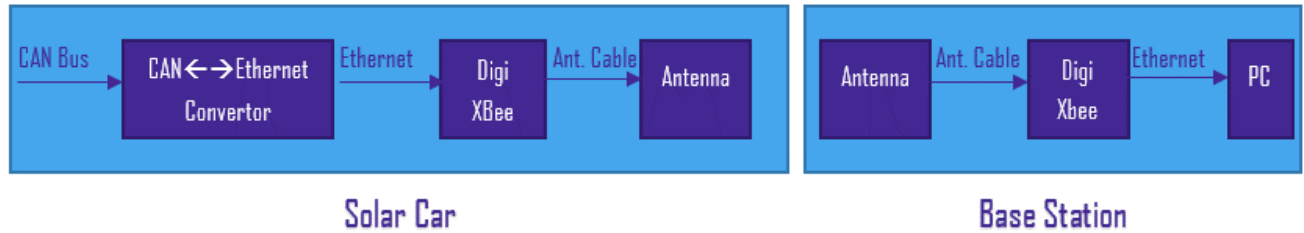


Figure 12: Telemetry system for SC7

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.

Gain Plots

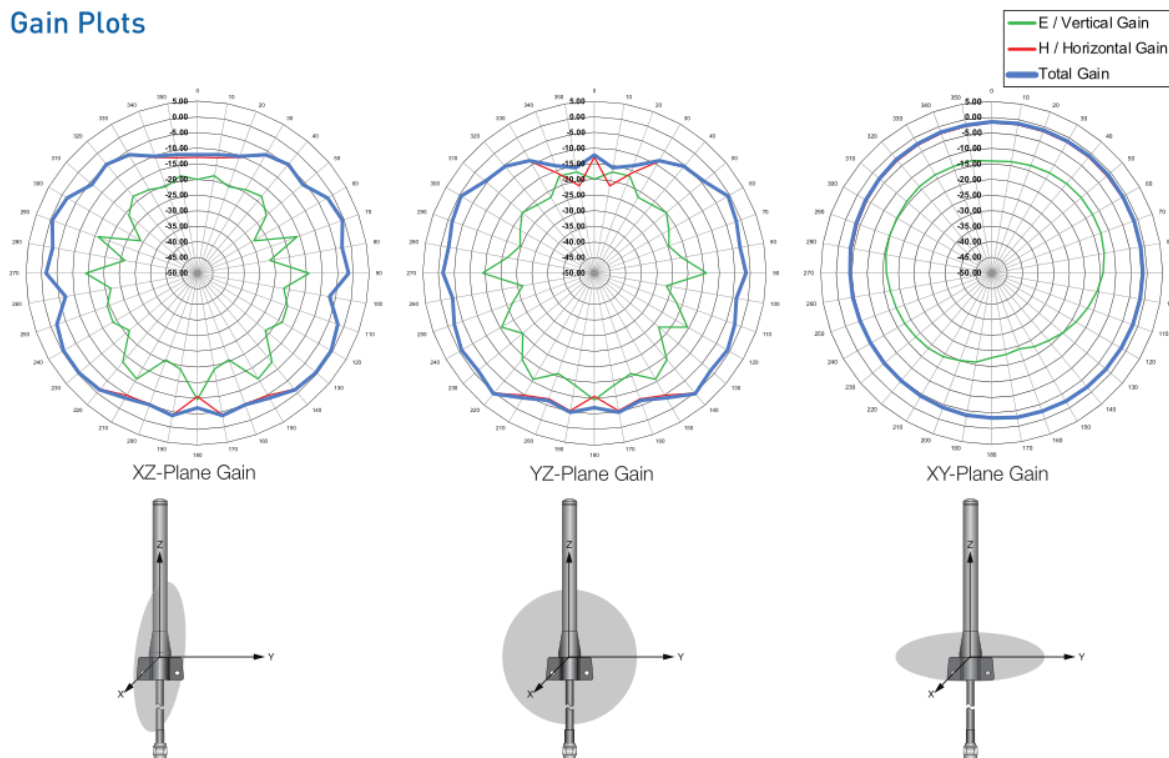


Figure 13: The ANT-916-ID gain plot shows that it is fairly omnidirectional

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