www.orionbms.com

Orion Jr. 2 BMS Operation Manual

The Orion Jr. 2 BMS by Ewert Energy Systems is designed to manage and protect lithium ion battery packs up to 48v nominal (maximum voltage never to exceed 60V at any time). The Orion Jr. 2 BMS is built on the same technology as the standard Orion BMS product line, but it is smaller and lighter and is specifically designed with features for stationary and light mobile applications such as solar & wind storage, UPS systems, golf carts, forklifts, scooters and more.

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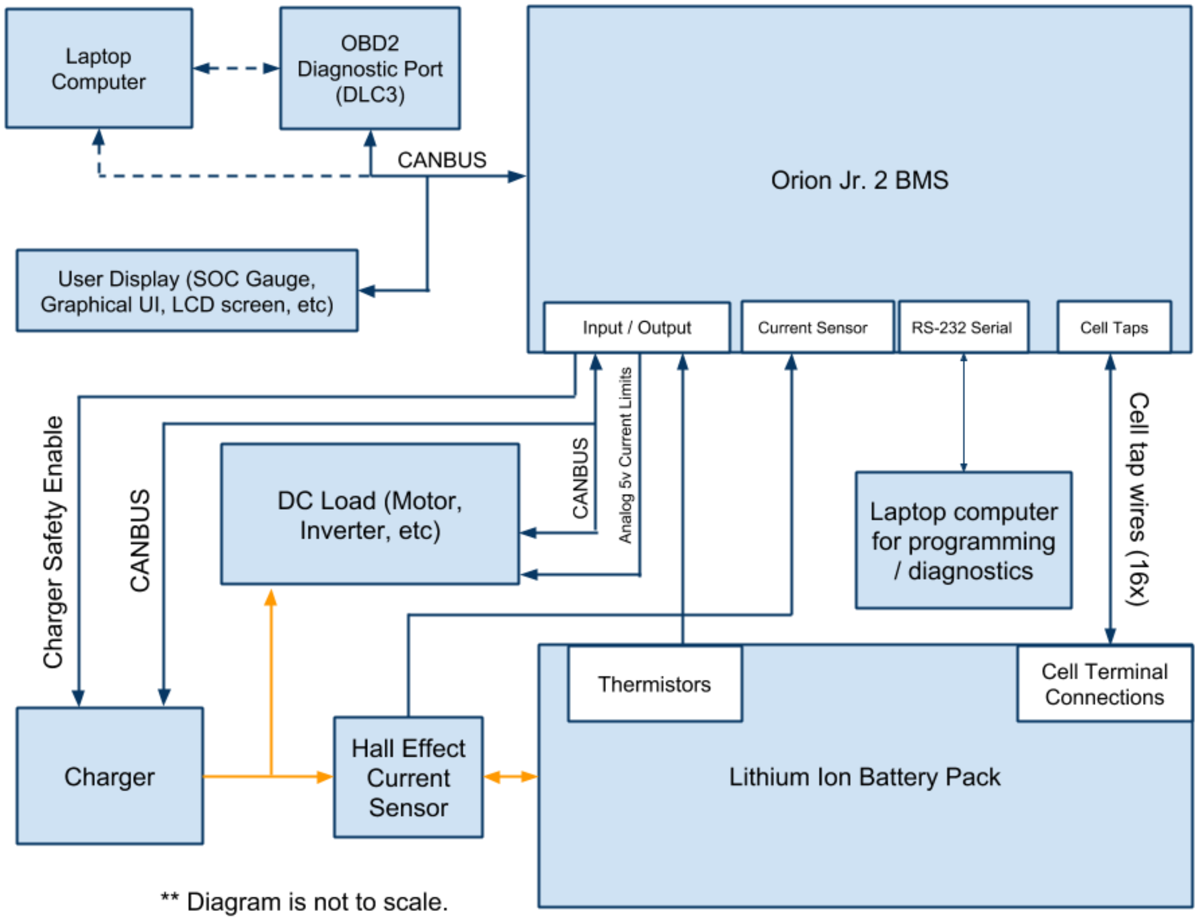
Overview of Theory of Operation



The Orion Jr. 2 BMS protects and monitors a battery pack by monitoring sensors and using outputs to control charge and discharge into the battery. The BMS measures inputs from cell voltage taps, a hall effect current sensor, three thermistors, and a multi-purpose input. Using the programmed settings, the BMS then controls the flow of current into and out of the battery pack through broadcasting charge and discharge current limits via the CAN bus, analog reference voltages, or simple on/off digital signals depending on which style is appropriate for the application. The BMS relies on the user to integrate the BMS with other external devices in a manner such that the current limits set by the BMS are respected in order to protect the batteries. During and immediately after charging, the BMS will balance the cells using internal shunt resistors based on the programmed settings.

The Orion Jr. 2 BMS unit monitors the voltage of each individual cell (through the cell tap wires) to ensure cell voltages remain within a specified range. Using the collected information, which includes parameters such as minimum and maximum cell voltages, temperature, and state of charge, the BMS calculates amperage limits for both charge and discharge. These charge and discharge current limits are then transmitted to other external devices digitally via CANBUS, via 0 to 5 volt analog signals, or via on/off outputs. The BMS also calculates the state of charge of the battery pack and monitors the state of health of the individual cells and battery pack.

Setting up the BMS

Wiring

Please see the wiring manual for information regarding wiring the BMS into the application. The wiring manual can be downloaded from www.orionbms.com/downloads.

Software

Please see the software manual for information on setting up specific software parameters and battery profile information. The BMS must be connected to a personal computer using the RS-232 serial interface (CAN enabled units may use a CANdapter CAN to USB adapter) and programmed using the Orion Jr. 2 BMS software utility before it can be used. The settings profile must be setup correctly for the specific battery used and the application. The settings profile controls parameters such as maximum and minimum cell voltages and external interfaces such as CAN interfaces and digital I/O. The software and software manual can be found at www.orionbms.com/downloads.

Testing

After setting up the BMS or making any changes to the BMS settings or external hardware, the entire setup should be tested to ensure that it is functioning properly. This is particularly important with respect to any potentially catastrophic failures, such as failures that would lead to over charge or over discharge. It is the responsibility of the user to verify that the BMS is programmed and operating correctly with the application. At a minimum, the user should perform testing to ensure the following conditions are working properly:

1. Ensure that the BMS is setup in such a manner than testing will not cause immediate danger to the battery pack.
2. Ensure that cell voltages are being read correctly and that no critical fault codes are present. The BMS cannot properly read cell voltages if unit and batteries are not wired correctly. Double checking cell voltages with a multimeter will help verify that the BMS is measuring voltages correctly.
3. Ensure that the current sensor is reading the correct values and that current going into the battery pack (charge) shows up as negative and that current leaving the battery pack (discharge) shows up as positive.
4. If the charge enable, discharge enable, or charge safety outputs are used (physically or transmitted digitally), ensure that they are operating by carefully monitoring the battery pack during the first full cycle (full charge and discharge) to check that cutoffs are properly working for all used outputs. Keep in mind that conditions are usually only triggered when the pack is totally charged or totally discharged. Particular attention should be paid to make sure the BMS is able to properly shut off any connected battery charger or any other source or load.
5. If charge and discharge limits are used (either via CAN or analog outputs) ensure that they behave as expected over the first full charge and discharge cycle and that any devices that must enforce those limits are actually respecting them.

How the Orion Jr. 2 BMS Works

(Detailed Theory of Operation)

Changing and Uploading Settings

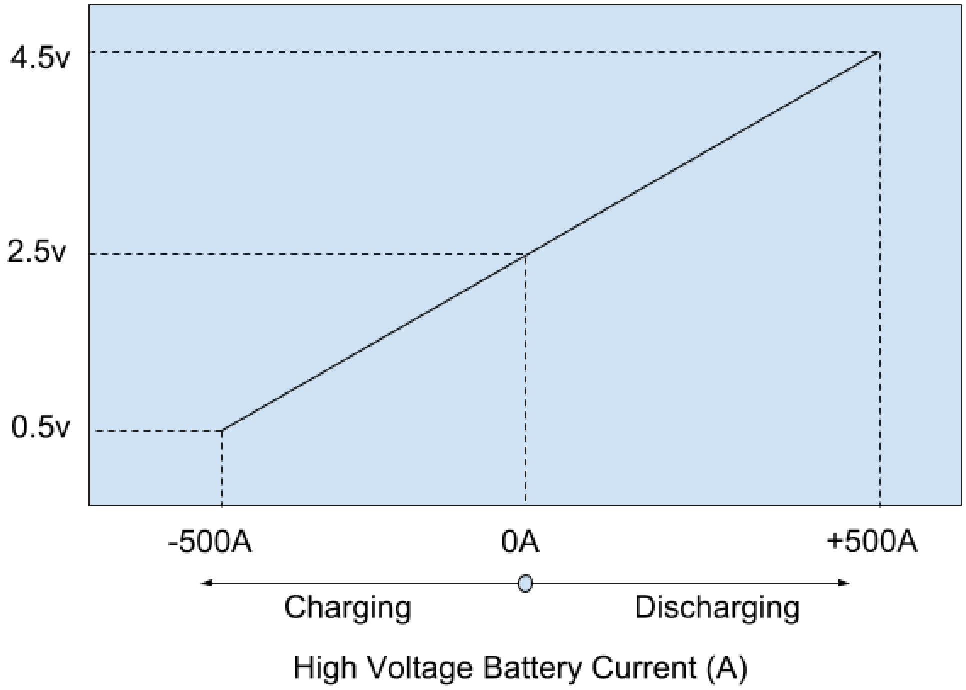
The Orion Jr. 2 BMS must be programmed in order to operate. A complete set of settings is called a pro-file. Settings are edited on a personal computer using the Orion Jr. 2 BMS Utility software and then are “uploaded” to the BMS via RS-232 serial (or via CANBUS). Profiles can optionally be locked into the BMS with a password to prevent end users from modifying or viewing settings. Uploading and downloading settings is normally done over the RS-232 serial interface. If using a computer which does not have a native RS-232 serial port, a serial to USB adapter may be needed (not sold by Ewert Energy). Programming over the CANBUS requires a CANBUS enabled Orion Jr. 2 BMS and the use of a CANdapter (a CAN to USB adapter) sold separately by Ewert Energy Systems. Setting profiles can also be downloaded from the BMS into the BMS utility to be edited on a personal computer

Basic Data Collection

The Orion Jr. 2 BMS collects data from several different sensors for use in calculations and decision making.

Cell Voltages - First and foremost, each cell’s voltage is measured approximately every 30 mS by sensing the voltage at the cell voltage tap connector. The BMS measures the difference in voltage from one tap wire to the next to measure a cell's voltage. Unless busbar compensation has been configured, the BMS will display and use the actual measured values for cell voltages (otherwise compensated values are used). Only the cell voltages which the BMS has been programmed to monitor in the cell population table in the settings profile are monitored while the other cell voltages are ignored.

Current (Amperage) - The current going in and out of the battery pack is measured every 8mS using the external hall effect sensor. The hall effect sensor is clamped around a wire carrying all current into and out of the battery pack and converts the measured amperage into two 0 - 5 volt analog voltages. One channel is used for measuring smaller amperages to ensure high resolution for small currents and the other channel is used for measuring larger currents. These two analog voltages are measured by the BMS and converted into an amperage value which the BMS uses for various calculations. The diagram below demonstrates how the feedback voltage from the larger channel correlates with the actual current being measured (a 500A sensor is used for demonstration purposes).



This figure demonstrates the relationship between the voltage output and current measured on the current sensor

The currents sensors sold with the Orion Jr. 2 BMS are available in sizes up to 1000A. The BMS can be configured to use 2 parallel current sensors to measure amperages up to 2000A, however the maximum recommended size is 1000A. Current sensors sold with the BMS are able to measure amperages up to 120% of their rated maximum, though accuracy is reduced above 100%.

Current sensor data is used in calculating the battery pack's state of charge (via coulomb counting) and ensuring that the attached application is staying within the correct current limits. The measured current is also used in calculating the internal resistance and health of the cells in the battery pack.

Temperatures - The BMS measures battery temperatures directly from up to 3 thermistors to determine the average temperature of the battery pack. If additional temperature sensing, such as measuring the temperature of each individual cell, is required, the Orion Jr. 2 BMS can be connected to a thermistor expansion module which can allow measuring up to 80 thermistors. Thermistors on both the main unit and any expansion modules may be left 'unpopulated' meaning that the BMS will ignore the value of those thermistors. This allows the BMS to be configured to use as few or as many thermistors as necessary. The thermistor expansion module is connected to the Orion Jr. 2 BMS through two of the analog thermistor inputs on the BMS or via CANBUS if the BMS is CAN enabled.

Total Pack Voltage - The Orion Jr. 2 BMS measures the total pack voltage by summing up the individual cell voltages.

Other Inputs - The BMS has the ability to sense the status of the CHARGE power supply. The BMS uses this input to determine what mode the BMS is in. The BMS also has a multi-purpose input which can be used for various functions, including monitoring the status of the READY power source if necessary.

CHARGE and READY Modes

The BMS has two modes of operation: charge mode and ready mode. The BMS will enter into charge mode any time > 9V is applied to the CHARGE power pin, regardless of whether READY power is also present or not. The following functions are enabled (or change) when the BMS is in CHARGE mode:

1. The charger safety output is allowed to turn on if enabled and if all criteria have been met.
2. The BMS will cap the state of charge to the value specified as the "Charged SOC" percentage. Even if the battery is charged in such a way that would normally cause the SOC to rise above this value, the value will not exceed the "Charged SOC parameter" while the BMS is in charge mode.
3. When any cell voltage reaches the maximum cell voltage (resulting in the BMS turning the charger off), the BMS will immediately adjust the state of charge to the "Charged SOC" value since the BMS knows that the battery pack is fully charged at this time.
4. The cell balancing algorithm is enabled and will begin balancing as soon as any cell voltage goes above the "Start Balancing" voltage. Balancing will continue until all cell voltages are balanced to within the balance delta voltage parameter. See the “How Balancing Works” section for more information on cell balancing.
5. The maximum possible current limit for charging is limited to "Maximum Amperage While Charging."
6. The maximum allowable cell voltage is limited to the "Max. Voltage While Charging" parameter.

Charge and Discharge Current Limits

For Lithium-ion cells, limiting cell voltages to within a specified voltage range is essential for protecting the cell from damage. However, there are many other parameters, such as temperature and current limits, which must also be monitored to protect the cells. To be able to control more than one parameter at once, the BMS incorporates different parameters into a maximum allowable charge and discharge current limit. Charge and discharge limits can be thought of as the realistic maximum amperage limits that a battery can discharge or charge at any given moment (expressed in 1 amp increments). Current limits are especially useful for variable current applications such as light mobile applications, because they allow these applications to slowly reduce current as a battery pack is emptied and therefore increase the usable range of a battery pack.

The charge and discharge current limits can be transmitted digitally from the BMS to other devices if the external device supports this. For example, most CANBUS enabled motor controllers and CANBUS enabled battery chargers support this. When a motor controller receives the current limit from the BMS, the motor controller knows that it cannot exceed the maximum current limit sent by the BMS even if the operator of the throttle calls for more power. *Because the BMS incorporates many factors into the maximum current limit, ensuring the current does not exceed this calculated current limit also ensures all the other associated battery parameters (such as minimum cell voltage, temperature, maximum C rate, minimum state of charge, etc) are enforced.*

While some motor controllers or chargers don’t support CANBUS, they may support an analog voltage input that represents the current limit. The Orion Jr. 2 BMS has 0 to 5 volt analog outputs which represent the maximum current limits in an analog voltage. This operates the same way as the CANBUS support, but is less accurate and less desirable than CANBUS control. If the 0 to 5 volt analog outputs are used, it is essential to ensure that the BMS and the external device share the same ground and that they are used in conjunction with the charge enable, discharge enable, or charger safety outputs depending on the exact use.

When a load does not support variable current limiting and can only be turned fully on or fully off (such as a DC to AC inverter), the BMS must operate in an on/off mode to control the load. In this case, the BMS still uses the charge and discharge current limits as the basis for making decisions about when the BMS will allow charge or discharge. The relay outputs will turn off whenever the associated current limit drops to 0 amps at any point. The BMS's decision whether to allow charge or discharge is available on the CANBUS and also on the charge enable and discharge enable outputs. The exact conditions for this are discussed in the Relays section of this manual.

How the BMS Calculates Current Limits

The charge and discharge limits are both calculated using the same methodology. The charge current limit takes into account the settings and parameters related to charging and the discharge takes into account the settings and parameters related to discharging. For simplicity, all criteria described below are for the discharge current limit. However, the same methodology applies to the charge current limit.

The BMS starts the current calculation by loading the maximum continuous discharge current limit programmed into the BMS. This setting is the maximum continuous discharge rating that the cell can sustain safely. The maximum current a cell can discharge is defined by the cell manufacturer, and the value in the BMS should never exceed the maximum limit given by the cell manufacturer, though in some cases, it may be desirable to use a lower value than specified by the cell manufacturer for increasing the lifespan of the cells.

The above calculations establish the absolute maximum allowable current under ideal conditions. However, the BMS may reduce those limits further for several reasons. If any of the below calculations result in a calculated current limit lower than the absolute maximum, the BMS will use the lowest of the calculated limits as the current limit.

1. ***Temperature*** - The BMS will lower the current limits based on the temperature limitations programmed into the BMS profile. The temperature limits are set by specifying a minimum and maximum temperature to start de-rating current and then a number of amps per degree Celsius to de-rate by when the temperature is outside of this range. Minimum and maximum battery operating temperatures for cells are enforced by ensuring that the current limits are reduced to 0 amps at the minimum and maximum temperatures. Ensuring temperature limits are 0 amps at the minimum and maximum temperatures also ensures that under all situations the charge enable, discharge enable, and charger safety enable outputs are all off if a thermistor ever exceeds a maximum temperature or a minimum temperature. (Note: an exception is if a thermistor reads a value less than -41C or greater than 81C at which point the BMS will disregard the value of the thermistor as faulty.)
2. ***State of Charge*** - The BMS will lower the current limits based on the calculated state of charge of the battery pack. Just like the temperature settings above, the BMS can optionally reduce the maximum current limits based on the programmed values in the profile settings. In this case, for

the discharge current limit, a state of charge is specified where to begin reducing the discharge current limit along with a value of amps per percentage state of charge. For most applications, this feature is not used and should be disabled to prevent errant SOC calculations from altering the usable range of the pack unless there is a specific reason for enabling it. This feature may be required, however, if the battery pack must be kept within a certain state of charge.

3. ***Cell Resistance*** - The BMS reduces the current limit to ensure that, if a load or charge is placed on the battery pack, the load or charge would not cause the cell to exceed the maximum cell voltage or drop below the minimum cell voltage. This calculation uses the internal resistance of the cell and the open circuit voltage of the cell. This can be thought of as an ohm's law calculation where the BMS is solving for the maximum possible amperage that will still keep the cell voltage inside the safe range. This calculation preemptively keeps the cell voltage within specifications and also results in a 0 amperage discharge or charge current limit in the event a cell voltage drops below the minimum or goes above the maximum voltage respectively.
4. ***Pack resistance*** - If enabled, the BMS performs the same calculations as in point 3, but for the minimum and maximum pack voltages and reduces current limits to maintain these values.
5. ***Cell Voltage*** - In the event that the above calculation were to ever be inaccurate due to incorrect data such as an incorrect cell resistance or incorrect open circuit, or if the current limit is ignored by the external device, the BMS contains a backup algorithm for reducing the current limits if a cell voltage limit is exceeded. If the BMS measures a cell voltage above the defined maximum cell voltage or below the defined minimum cell voltage, the BMS will cut the respective current limit by one fifth of the current limit at the time the out of range cell voltage is measured in an attempt to restore the voltage to a safe level. If this fails to bring the cell voltage back to within the defined range, the BMS will again cut the current limit by one fifth of the maximum continuous amperage and try again. This will happen very rapidly up to a total of five times. If the voltage is still outside of the range, the BMS will have reduced the current limit to zero amps which prohibits all discharge or charge (depending on if the cell voltage was too low or too high respectively.) *This ensures that under all circumstances, if a cell voltage is ever above the maximum limit or below the minimum limit, the BMS will always have a zero amp charge or discharge current limit which prohibits all charge or all discharge respectively.* This ensures that the charge enable, discharge enable and charger safety enable outputs are all off if a cell ever exceeds a maximum cell voltage or drops below a minimum cell voltage.
6. ***Pack Voltage*** - If enabled, the BMS performs the same calculations as in part 5, using the pack voltage limits rather than the cell voltage limits. Total pack voltages are calculated based on the sum of the individual cells. For best reliability, pack voltage limiting should only be used when it is necessary to restrict the pack voltage more than the individual cell voltage restricts the pack voltages. For example, if a pack has 10 cells and the cell voltage limits are 2.5v and 3.65v, the pack voltage is already inherently limited to 25v to 36.5v.
7. ***Critical Faults*** - In the event that the BMS detects a critical fault relating to the ability of the BMS to monitor cell voltages, the BMS will go into a voltage failsafe condition. The specific possible causes of the voltage failsafe mode are defined in the "Understanding Failure Modes" of this manual. If one of the critical faults that cause a voltage failsafe condition occurs, the BMS will immediately start gradually reducing both the charge and discharge current limits to zero which prohibits all charge and discharge. The gradual reduction allows a vehicle time to pull over and safely stop. The speed at which the limits are reduced is programmable in the BMS settings. The relay outputs will be turned off only after the gradual de-rating has occurred.

Diagnostic information is provided from the BMS in the live text data tab in the utility as to which of the above reasons the BMS is limiting current.

Selecting Current Limit Settings

The Orion Jr. 2 BMS utility has data for many common cell types already pre-loaded into the utility. These can be accessed by using the Profile Setup Wizard in the BMS utility. For cells which are not listed, or if custom settings are required, the following guidelines may be helpful for selecting proper values.

Maximum Continuous Amperage Setting - The continuous maximum amperage should be set at or below the maximum allowable continuous amperage as specified by the cell manufacturer. In some cases, it is desirable to use a lower value than what the manufacturer specifies in order to extend the lifespan of the cells. In some cases the manufacturer will specify a “C” rate. To convert a “C” rate to an amperage, simply multiply the C rate by the amp hour capacity of the cell. For example, a 100 amp hour cell with a 2C continuous discharge rating is has a maximum continuous discharge rate of 200 amps.

Current Limit Temperature Settings - All cell manufacturers specify a minimum and maximum operating temperature for charge and discharge. Typically, the temperature range for charging is more restrictive than the temperature for discharging. Some cells are not permitted to be charged below a certain temperature. For example, many iron phosphate cells cannot be safely charged below freezing. Additionally, it may be desirable to further limit the amperage at low or elevated temperatures since high charge and discharge rates at such temperatures may reduce the lifespan of the cells.

Temperature limits must ensure that no charge or discharge is permitted below the minimum or above the maximum temperatures. For both charge and discharge settings, select a temperature at which the maximum amperage should be reduced. This value should be programmed into the BMS utility, and an amps per degree Celsius value should be calculated to ensure that the slope of the line intercepts zero amps at the desired cutoff temperature. This should be done for both high and low temperature limits for both charge and discharge current limits. *Warning: If the temperature de-rating line does not intercept zero, the BMS will not protect for over or under temperature!*

In a very limited number of applications, it may be necessary to allow a minimum charge or discharge value at all temperatures. If this is the case, the “Never reduce limit below xx amps for temperature alone” setting can be used. *Warning: if the “never reduce limit below” setting is anything other than zero, the BMS will not protect for over or under temperature!*

Note: While the maximum amperage can be specified for a specific temperature, the BMS may still use a lower current limit if it determines a cell resistance cannot support a current limit. Most lithium ion cells have a significantly higher resistance in the cold and may be limited by cell performance rather than by these settings.

State of Charge Current Limit Settings - These settings allow the BMS to gradually reduce the maximum allowable amperage based on the calculated state of charge of the battery pack. If this line intercepts zero amps, the BMS will prohibit all charge or prohibit all discharge if the SOC is higher or lower respectively than the state of charge where the line intercepts zero amps.

While this feature can be helpful for certain applications, it should be left disabled when not required. State of charge of the battery is calculated by the BMS. It is possible for this calculation to become inaccurate for a variety of reasons, such as a current sensor fault, incorrectly set SOC drift points, a low capacity cell, or if the BMS memory has been reset since the last full charge or discharge. If this feature is used, care must be taken to ensure that the SOC drift points are setup correctly and that the application will operate safely and appropriately in the event that the SOC calculation becomes inaccurate.

Other related settings - Cell resistance settings are not directly related to the current limits, but they can impact the current limits. The nominal cell resistances are loaded into the BMS when it first turns on and are used initially for the cell resistance current limit calculation. The BMS will switch to using measured cell resistances as soon as that information is available, but current limits may be incorrect when the BMS is first turned on if the default resistance settings are incorrect.

State of Charge Calculation

Note: The Orion Jr. 2 BMS cannot calculate state of charge without a current sensor!

The Orion Jr. 2 BMS calculates a battery pack's state of charge (SOC) primarily by coulomb counting, or by keeping track of how much current has entered or left the battery pack. This method requires the use of a current sensor and generally tracks the state of charge of the battery pack quite well provided that the capacity of the battery is known and the current sensor is accurate. While coulomb counting is an accurate method, there are several things that can cause this calculation to become inaccurate. These things include inaccurate current sensors, cells with a different capacity than expected (e.g. from low temperature or weak cells), or the BMS memory being reset or reprogrammed.

To deal with these issues, the BMS has an SOC correction algorithm which compares measured open circuit cell voltages to known state of charge points. These points are called "drift points" and are programmed into the BMS when it is setup. Drift points are specific voltages that are known to correlate to a specific state of charge and will vary from chemistry to chemistry. If the open circuit cell voltage is measured to be at one of these specific "drift points," the BMS knows what the state of charge of the battery is supposed to be. In the event that the BMS's calculated state of charge is higher or lower at one of these points, the BMS will adjust the calculated state of charge to the correct value.

Drift points are usually selected at locations along the cell's discharge graph where the cell's state of charge is obvious in a manner to avoid drifting incorrectly. For iron-phosphate cells, this means that really only the upper 10-15% and lower 10-15% of the cell can be used for drift points due to the flat shape of the discharge curve. For other chemistries, additional points throughout the full range of state of charge may be possible, improving the accuracy of the drifting.

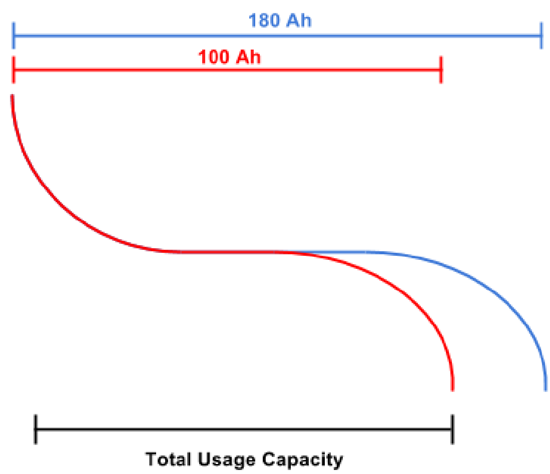
Drift points are specified to only drift up or only drift down. The BMS will always uses the highest open circuit cell voltage and lowest open circuit cell voltage for these calculations such that that the pack is properly protected.

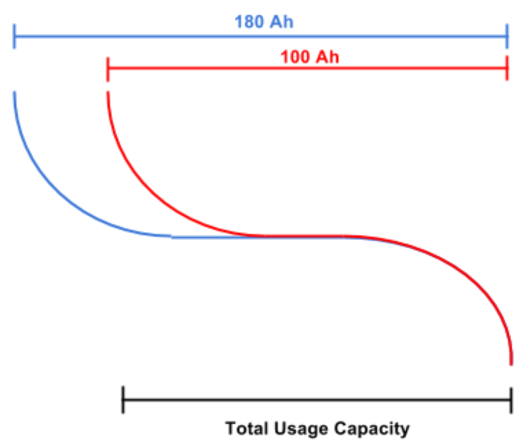
In addition to the drift points that are programmed in, the BMS also knows what state of charge the battery is at when a charge cycle completes. Since the BMS is controlling the battery charger, the BMS will set the state of charge to the "Charged SOC" value to indicate a full charge whenever it turns the charger off due to a full charge. It should be noted that this only occurs when the BMS is in CHARGE mode and actually turns the charger off due to a full charge.

Why SOC Correction Drifts Happen

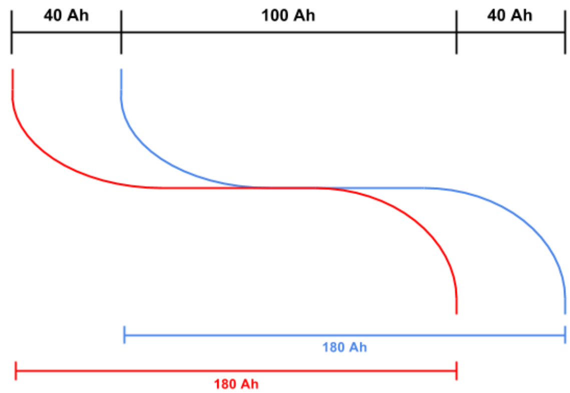
Correction drifts generally occur for one the following reasons:

1. A drift may occur if one or more cells within the battery pack has a lower capacity than the others. The battery pack is only as strong as the weakest cell, because the weakest cell cannot be over charged or over discharged. If a cell has a lower capacity than the rest of the pack, the weak cell will cause the BMS to correct the state of charge on the high end or on the bottom end depending on how the cell is balanced. The 2 images below show a top balanced and bottom balanced iron phosphate cell. A drift will occur at 100 amp hours in both cases since the weakest cell is only 100 amp hours. The remaining 80 amp hours is not usable since one cell's voltage would exceed the allowable range.





2. A drift may occur if the battery pack is out of balance. If one cell is at 70% state of charge, and another cell is at 30% state of charge, less than 50% of the battery is usable without one of the cells getting too high on the high end or too low on the low end. This limits the usable range of the battery and results in a lower capacity than the BMS is expecting, which requires the BMS to adjust the calculated state of charge. During discharge, as the BMS sees the lowest cell's open circuit voltage drop to a known drift point, the BMS will correct the state of charge showing that the battery is nearly depleted. The same will happen during charge due to a high cell voltage. In the example below, while the cells are 180 amp hours in size, two cells are 40 amp hours out of balance with each other and only 100Ah is usable before a cell voltage becomes too high or too low. In this example, SOC corrections would occur at the both ends of the 100Ah usable range. This would be due to the blue cell on the high voltage and the red cell at low voltage.



3. A correction drift may occur if the capacity of the cells has changed due to cold temperatures. Some cells (notably iron-phosphate cells) have a restricted range in the cold which can be as little as 50% of the normal capacity.

4. A correction drift may occur if the calculated SOC does not actually match the state of charge of the battery pack, which can be a result of an inaccurate current sensor. This can also happen if certain settings on the BMS have been changed, if the BMS has been reset by software, or if the BMS has just been connected to the battery pack for the first time. When the BMS is powered up for the first time, it will not know the state of charge of the battery pack. In these cases, the BMS defaults to 50% state of charge, and a state of charge drift is almost certain to occur within the first cycle to correct the state of charge unless the battery happened to be at exactly 50% state of charge.

5. If the pack capacity is lower than the capacity programmed into the BMS unit.

6. If the minimum and maximum cell voltages are restricting the usable range of the pack and the SOC settings programmed into the BMS don't reflect the lower usable range.

7. Inaccurate open circuit voltage calculations due to an incorrectly installed or defective current sensor.

Note: The Orion Jr. 2 BMS cannot calculate state of charge without a current sensor! If a current sensor is not connected, the Orion Jr. 2 BMS will derive the state of charge based strictly on instantaneous cell voltages. This method is very inaccurate - the state of charge calculation may oscillate wildly and should not be used for any calculations. This mode exists only as a backup algorithm for specific applications and is not designed for normal use.

Determining State of Charge Correction Drift Points

Every battery chemistry will have different state of charge drift points. Unfortunately, cell manufacturers typically do not provide this information and it often has to be determined either from experimenting or from performing careful analysis and running charge and discharge cycles. While the points can be established, some tweaking may be required to maximize performance.

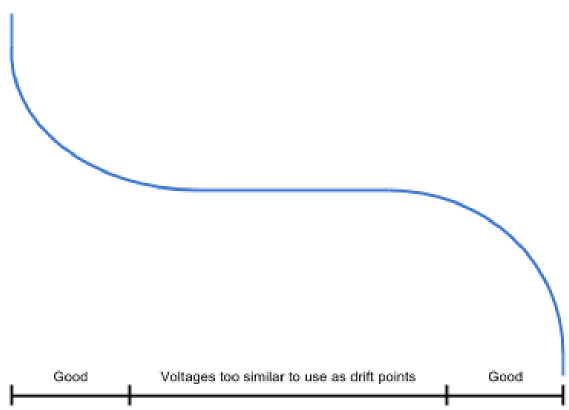
Ewert Energy maintains a database of state of charge drift points for many common cell types. This information can be automatically entered into the battery profile by using the "profile setup wizard" in the BMS utility. For cells that are not in the database, Ewert Energy offers a service to characterize cells.

This service will produce default settings for cell resistance measured at different temperatures, SOC settings, and standard voltage settings. This service requires at least one sample cell and the manufacturer datasheet. For common cells which are not in the database yet, the service may be discounted or free when a sample is provided.

To determine approximately where the drift points should be, take a sample cell and charge it up to 100% SOC (following manufacturer's recommendations). After the sample cell is fully charged, discharge it to 0% (following manufacturer specs for the minimum cell voltage and discharge rate) at a very low amperage to get as close to an open cell voltage curve as possible. Once the discharge is complete, graph the cell voltage vs. amp hours discharged, and there should be a fairly clear discharge “curve” (can be very different shapes depending on the chemistry.) From this data, approximate SOC to voltage data can be gathered. Some trial and error may be necessary to fine tune the drift points.

While datasheets from the battery cell manufacturer may be useful in calculating rough drift points, they often contain graphs with instantaneous voltages at higher C rates which have added voltage drop from the cell resistance included. The values for SOC drift points are the open circuit voltage (voltage without a load applied) of a cell.

Drift points should be established at places on the discharge curve where the voltage change is most significant. For example most iron phosphate cells stay at 3.3v for the majority of the discharge curve and suddenly start to rapidly drop at 3.0v. 3.0 volts is a good place to set a point. If the drift points are set too close together (e.g. if a drift point is set at 3.4v and 3.2v and the battery spends most of its time at 3.30-3.35v) then they may trigger SOC drift prematurely as the open cell voltage of a battery will drift up and down slightly under load due to a temporary voltage depression (e.g. under a 100A load a battery’s open cell voltage may drop from 3.3v to 3.2v, though it will gradually return to 3.3v once the load is removed).



A state of charge drift point consists of two items, an *open cell voltage* and a corresponding *state of charge* percentage. When a cell’s open cell voltage equals the open cell voltage of the programmed drift point, then the state of charge will drift to the state of charge associated with the programmed drift point. Additionally, drift points are specified as “drift up only” and “drift down only”, indicating which direction they are allowed to affect drift (e.g. If a drift point at 80% SOC is set to 3.5v and is flagged as “drift up only”, then it cannot cause the SOC to drift down to 80% if the open cell voltage is below 3.5v).

It is important to have a sufficient number of state of charge drift points to both protect the battery and to maintain an accurate SOC calculation. Typically at least 4 points are used (2 on the top end and 2 on the bottom end of the curve) though this is not a minimum. For batteries which do not have a large flat portion of the "curve", additional points may be used in the middle of the battery for increased accuracy. Having a correct SOC calculation is important for maintaining the battery in a specified range. However, regardless of the state of charge calculation, the Orion Jr. BMS can still protect the battery pack from damage from over-voltage and under-voltage via monitoring the instantaneous cell voltages.

The state of charge drift points in the Orion Jr. 2 BMS are not jump points. This means that when the open cell voltage on a particular cell reaches a drift point, it will not immediately jump to the provided state of charge. Rather, it will gradually "drift" up or down until the battery pack state of charge is equal to the target state of charge. This additional hysteresis helps make the transition smoother as well as helps eliminate "partial" drifts where the open cell voltage may only very briefly exceed the drift point voltage.

The BMS allows for State of Charge drift points to be flagged as "Drift Down Only" and "Drift Up Only". These are very helpful for situations where a battery's voltage may not stay constant at a given voltage for very long. "Drift Down Only" means that the BMS will only allow the given drift point to make the State of Charge go down (it won't make the SOC go up if the observed open voltage is higher). Likewise, "Drift Up Only" will only allow the SOC to go up and not down.

"Drift Down Only" and "Drift Up Only" are very useful settings for batteries that have a high surface charge (where the battery voltage may dip to a specific voltage but over time will creep back up). *The use of these settings is recommended for all drift points as most batteries will demonstrate at least some degree of surface charge.*

State of Health Calculation

The Orion Jr. 2 BMS determines the State of Health of the battery pack primarily by examining both the Internal Resistance and the observed capacity (measured in amp-hours) of the battery pack. As the observed capacity decreases from the nominal (starting) capacity and the internal resistance increases from the nominal capacity, the state of health will go down. This value is typically reflective of the age of the battery pack. However, defective cells or premature aging due to abuse, loose busbars or terminals, or improper wiring can also cause this calculated value to drop prematurely or incorrectly.

Every application will have different requirements for what state of health is acceptable. For stationary applications such as a light mobile vehicle, a lower state of health might be acceptable. For an application such as an electric vehicle the minimum state of health may higher, so the pack may need replacing sooner than in other applications. A minimum state of health threshold can be programmed into the BMS. If the state of health drops below this value, a weak pack fault code will get set. This fault code is informational only to indicate that the battery pack should be inspected and will not alter the behavior of the BMS in any way. Although the fault does not alter the behavior in any way, a high resistance cell or a cell with a lower capacity than expected could impact operation in other ways.

Internal Resistance

The Orion Jr. 2 BMS measures the internal resistance of each cell by measuring the relative change in voltage when a known load is applied to the cell. In order to calculate the internal resistance, the BMS depends on external changes in current. The BMS cannot directly measure the internal resistance without changes in current being applied to the cells, and if external changes in current are not available or not suitable, the BMS may not be able to calculate the resistance of cells. When the BMS is not able to measure the actual resistance, the nominal resistances programmed into the settings profile are used until an actual measurement can be obtained.

Internal resistance is the main reason cell voltages change nearly instantly when a load or charge is applied to the cell. When current is applied to the cell, the resistance inside the cell causes a voltage drop (or rise) with respect to the amount of current flowing through the cell. When the current stops flowing through the cell, the voltage will go back to the open circuit voltage. For example, if a battery has an internal resistance of 2 mOhm (0.002 Ohm) and starts off at 3.3v, the instantaneous cell voltage will be 3.5v while a 100A charge current is applied (a 0.2v voltage “drop” since 100amps * 0.002ohms = 0.2volts, E = I * R). When the pulse is finished, the instantaneous cell voltage drops back to about 3.3v. Knowing the internal resistance for each cell allows for the calculation of how much current a cell can handle before the minimum or maximum cell voltages would be exceeded. This information is also used in calculating the open circuit voltage of a cell, even when the cell is under load, which is used for state of charge correction drift points. Cell resistances are also useful for measuring the amount of energy loss. Internal resistance is often expressed in milliohms (mOhms) or one thousandth of an ohm.

How the BMS Calculates Internal Resistance

The Orion Jr. 2 BMS depends on external changes in current to be able to back calculate the resistance of each individual cell Therefore, the BMS does not initially know the cell resistances and will begin by using pre-programmed default resistances based on the temperature of the cells. To do this, the BMS takes the average temperature of the pack and looks up the nominal resistance for the cell for the average temperature of the pack in the nominal resistance table programmed into the BMS. The BMS uses the default value until a real measurement can be taken.

Only certain changes in current are used by the BMS for determining internal resistance. The changes in current must be sudden enough, large enough, and stable enough within a set amount of time for the BMS to use them in the calculation. A minimum of two changes of current are needed within a set amount of time for the BMS to update the resistance data. The calculated current trigger is generally a percentage of the total amount of the current sensor. The minimum value is generally about 20% of the value of the current sensor, but the minimums are adjusted automatically by the BMS based on other factors such as temperature as the cell may not be able to output enough power to meet the 20% standard threshold when cold.

The BMS will prefer to use calculated internal resistance values, but nominal resistance values must be programmed into the BMS as default values. The default values are used when the BMS is first powered up or when power has been interrupted to both power sources. Since temperature can significantly alter the internal resistance of a cell, the BMS will also use default values when a significant change in temperature has occurred since the last known calculated internal resistance value.

Determining Nominal Resistance

Internal resistances of cells change considerably based on temperature. Typically a battery will have a significantly higher resistance in colder temperatures than in hot temperatures. Lithium ion batteries tend to have an L-shaped resistance curve with the resistance increasing exponentially in cold / freezing temperatures and slowly approaching a lower resistance in extremely hot temperatures.

The Orion Jr. 2 BMS allows the user to specify the nominal resistance for each temperature range in increments of 5 degrees Celsius. This allows for using any type of different Lithium ion battery regardless of how unique its resistance curve is. It is important both for the protection of the batteries as well as the determination of cell health that these figures be as accurate as possible. Too high internal resistance numbers can cause the initial calculated current limits to be too low and can also cause the BMS not to set weak cell faults when it should. Internal resistance numbers set too low can result in false positive "weak cell faults" and the BMS initially calculating that a battery pack can supply a higher amperage than it actually can (the BMS would update the current limit as soon as current started to flow).

It is best, however, to test the resistance at least every 10 degree Celsius over the entire usable range if possible. After a few points are collected at different resistances, an exponential curve should begin to emerge and in some cases, it may be possible to extrapolate some data without testing at every 5 or 10 degrees Celsius.

Note: Internal resistances will be significantly higher at full state of charge and empty state of charge. When determining nominal internal resistance values, the resistance should be measured at a normal state of charge such as around 50%.

Ewert Energy offers a service for measuring internal resistance from sample cells at temperatures across the working range of the cell and turns this data into settings for the BMS profile. For more information about this service, please contact Ewert Energy.

To determine the nominal resistance for a battery at a given temperature the following procedure should be followed:

1. Charge the battery to an appropriate state of charge where the resistance is roughly the nominal resistance. Most lithium ion cells will have a significantly higher resistance at very high and very low states of charge and those areas should be avoided for calculations. For best results, repeat this procedure at several different states of charge.
2. Let the battery sit at the desired temperature for a period of time (can be several hours depending on the mass of the battery) without any current going in or out (resting).
3. Measure the voltage of the cell very accurately. This will be the Open Cell Voltage of the battery since there is no current going in or out.
4. Apply a known *constant* load to the cell.
5. After 10 seconds, take another voltage measurement.
6. Measure the actual amperage leaving the battery to increase the accuracy of the calculation.
7. Subtract the voltage reading from step #5 from the voltage reading from step #2 to get the Voltage Drop.
8. Divide the Voltage Drop by the measured amperage from step #5 to determine the 10 second DC internal resistance (DCIR) expressed in Ohms. (convert to milliohms by dividing by 1,000)

Example: Assume a battery is observed at 3.3v resting. A 20 amp load is applied to the battery at which point the measured voltage drops to 3.0v. The internal resistance can be computed by taking 3.3v - 3.0v = 0.3v / 20 = 0.015 Ohm or 15 mOhm at the specific temperature the reading was taken.

The Orion Jr. BMS itself can be used to perform these calculations when used in a controlled environment. Using the Orion Jr. BMS to determine internal resistances has the added advantage of being able to calculate the AC vs. DC internal resistance ratio as well: The same procedure is used above, but with the BMS measuring the cell voltages and current. Instead of a single 10 second pulse, a 10 second pulse should be applied first, followed by a series of 5 or so quick 1 to 2 second pulses. The addition of the 1-2 second pulses helps ensure that the BMS is able to accurately calculate the AC internal resistance. The manually calculated value after 10 seconds is compared to the value that the BMS calculates after all the pulses are complete. The difference between these two internal resistance values is the AC vs. DC resistance ratio.

Controlling Loads and Chargers

The Orion Jr. 2 BMS makes decisions about whether or not the battery pack can accept charge or discharge. As the BMS does not have integrated switches or contactors, the BMS unit cannot stop current flowing in or out of the battery pack by itself. Instead, it provides signals to externally connected devices instructing them to either turn on and off, and for devices which support it, it provides a maximum allowable current limit. *The BMS must be properly integrated with all current sources and loads connected to the battery being protected. Failure to do this may lead to a battery fire and/or permanently damaged cells.*

Devices typically fall under two categories. Devices that can only be turned on or off (such as DC to AC inverters) and devices which can be variably limited (such as motor controllers or many battery chargers.) While the BMS may be setup differently depending on which type of device it is controlling, the methodology for both is based on calculated current limits.

Digital On/Off Outputs (Relay Outputs)

Three on/off outputs are provided on the Orion Jr. BMS for controlling chargers and loads. Conceptually these outputs can be thought of as whether the BMS is allowing charge or discharge into the battery pack at any given time. All three outputs are open drain and are active low (pull down up to 175mA to ground when on). These outputs are on (pull down to ground) when discharging or charging is permitted. For more information on the electrical specifications and wiring procedures for these outputs, please see the wiring manual.

Each of the on/off relay outputs are designed to control different types of devices. Charge enable and discharge enable share the same algorithm for turning on and off while charger safety uses a slightly different algorithm. The discharge enable output is designed to control any load on the battery pack. Charger safety is designed to control a battery charger when used in a defined charging period where a user input starts the charging process such as when a vehicle is stopped and plugged in. The charge enable output is designed to control devices which may alternate between charging and discharging, such as regenerative braking in a vehicle or solar energy storage applications. It is also used when the

BMS must allow charge to re-occur once the battery pack has been discharged a certain amount, such as in solar, wind, and some standby power applications.

Criteria for all 3 relay outputs

All 3 of the relay outputs will turn off if their respective current limit reaches zero amps (charge enable and charger safety both use the charge current limit, while discharge enable uses the discharge current limit). In addition to other criteria, the charge current limit will always reach zero amps if any cell voltage exceeds the programmed maximum cell voltage, thereby turning off both the charge enable and charger safety outputs. Likewise, the discharge current limit will always reach zero amps if any cell voltage ever drops below the programmed minimum cell voltage, turning off the discharge enable output.

All 3 of these outputs can also be programmed to turn off if the measured current exceeds the current limit imposed by the BMS by a certain percentage that is programmed in (same percentage is used for all 3 relays). This feature must be enabled for each of the relays individually through the settings profile. This feature must be enabled for the BMS to protect against over-current. If the relay turns off due to the over-current condition, that specific relay will latch off until the BMS is reset or the power cycled. Note: Enforcing current limits is not designed to protect against short circuits and is not a replacement for fuses or circuit breakers. All battery packs must have suitable hardware over-current protection devices such as fuses or circuit breakers.

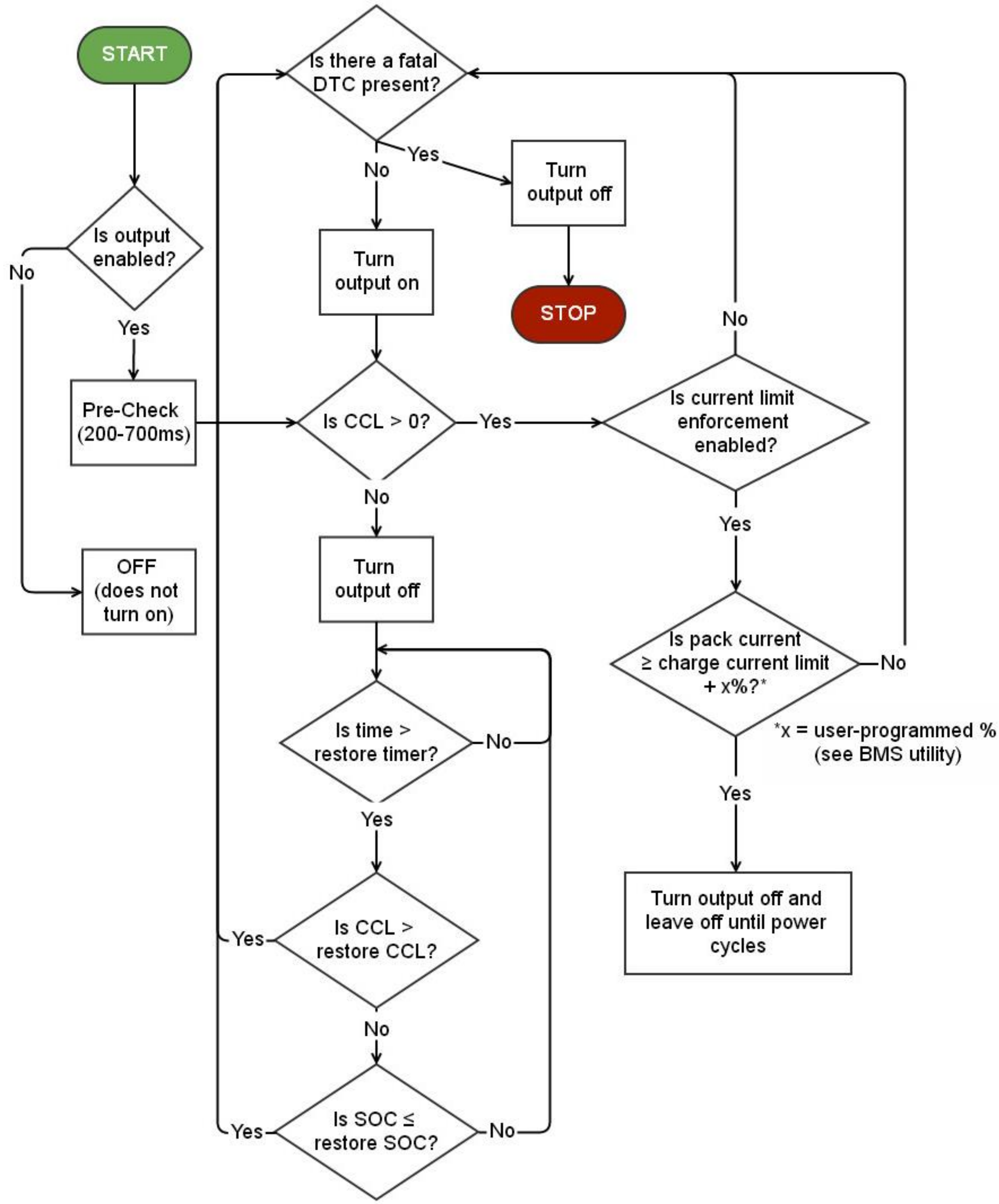
For all three relay outputs, minimum and maximum temperatures can be specified by ensuring that the charge and discharge current limit settings programmed into the BMS de-rate the maximum possible amperage to zero amps at the desired temperatures. The same can be enforced for state of charge. This, along with other programmable criteria for controlling the charge and discharge current limits, is discussed in more detail in the “How the BMS Calculates Current Limits” section above.

When the BMS turns off these outputs, charge or discharge must stop within a certain timeframe (about 500ms by default, though this value can be changed in the profile configuration settings under Fault Settings -> Current Limit Faults). If the BMS still measures current flowing into or out of the battery pack after this amount of time after the BMS has prohibited the respective action, the BMS will set a relay enforcement fault code. If this happens, the BMS will turn off all 3 of the relay outputs plus the multi-purpose enable output in a last ditch effort to stop all charge and discharge, and the outputs will latch off until the fault is cleared or the unit is power cycled / reset. (*Note:* The standard multipurpose outputs do not have this safety feature, and the status of those outputs is not affected by any fault status unless specifically chosen).

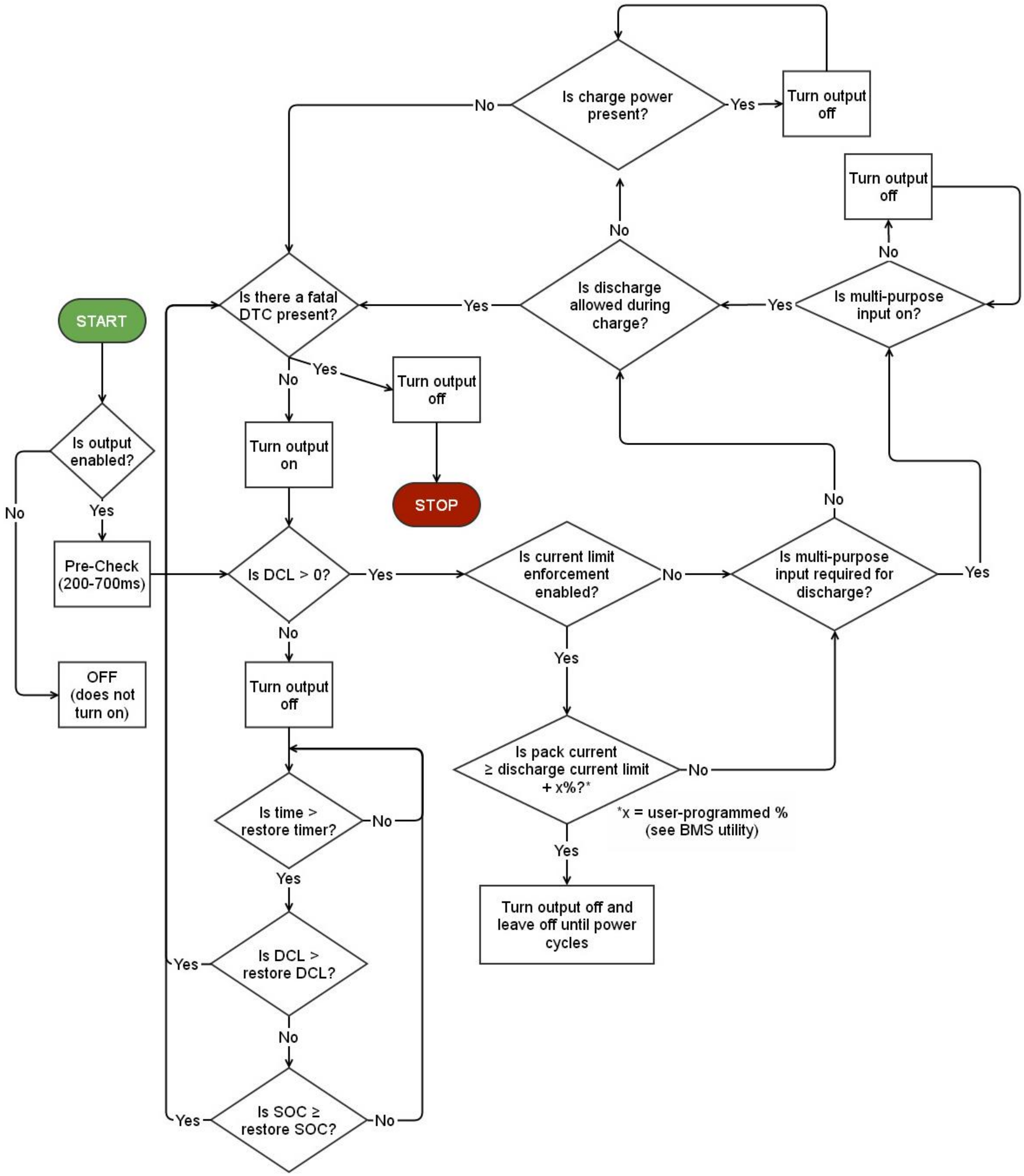
Once the relay outputs turn off due to the current limit being zero amps (and not due to a fault condition or over-current condition), they may be programmed to turn back on again after a minimum amount of time when certain criteria are met. By default the outputs will remain off until the BMS is power cycled or reset. The criteria for the charge enable and discharge enable outputs are the same, but charger safety is different.

Criteria for Charge Enable and Discharge Enable - After a minimum time interval defined in the profile settings, the outputs may turn back on based on state of charge or based on the charge or discharge current limits rising back up to a set value. They are turned on when either one of those conditions are met, though usually only one condition is used. Care must be taken to prevent oscillations, so values must be chosen far enough apart as not to allow the output to turn on again immediately. For solar, wind and standby power systems, the output is usually turned back on based on state of charge dropping at least 1% or 1.5% SOC. For applications requiring a certain amount of amperage to turn back on, turning the relay output back on based on the calculated current limit may be more appropriate.

Charge Enable Flow Chart



Discharge Enable Flow Chart

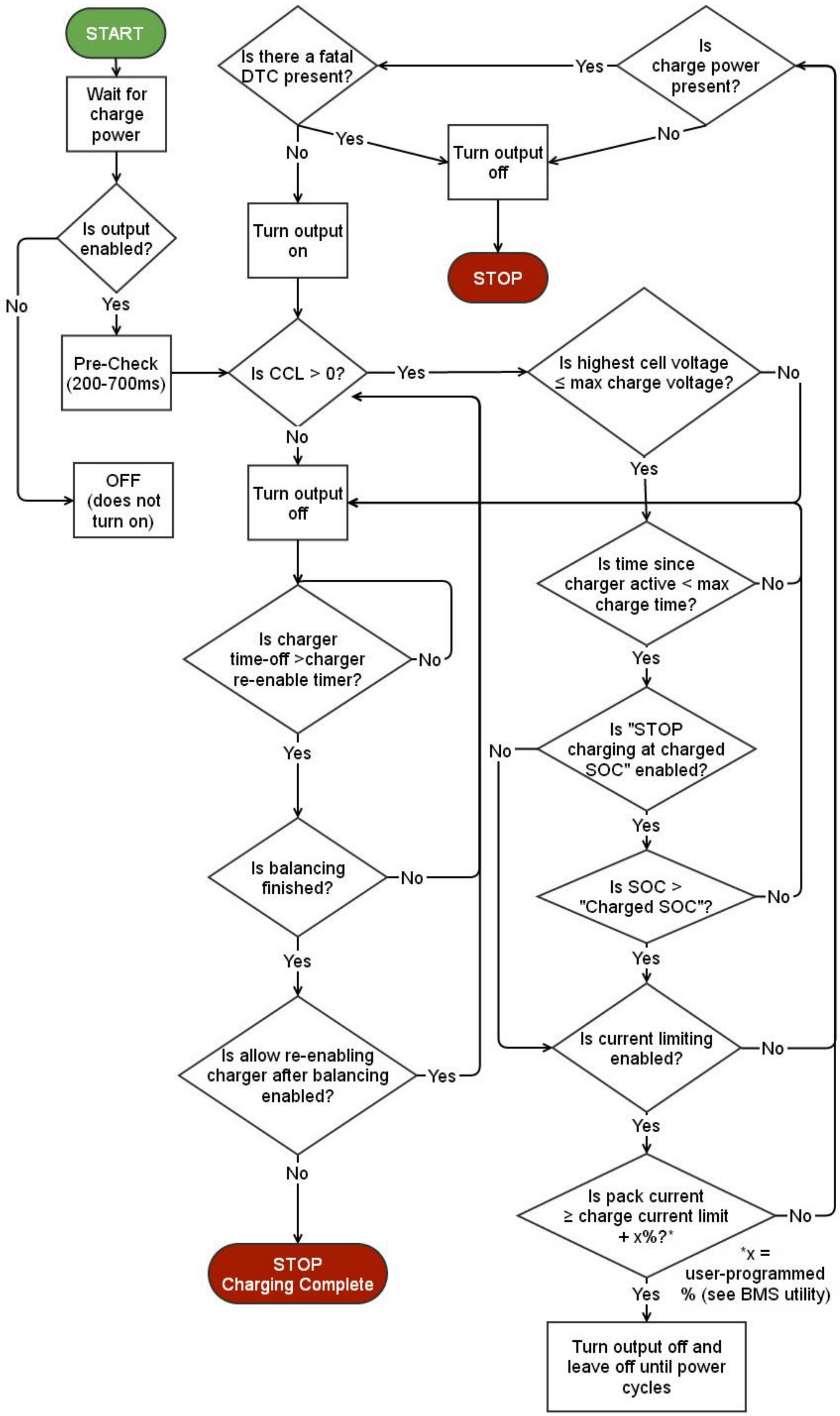


Criteria for Charger Safety - The charger safety output is only allowed to turn on when the BMS is in CHARGE mode. Once this output turns off due to a cell voltage reaching the maximum cell voltage, the BMS will adjust the state of charge and latch the charge current limit at zero amps since the battery is full. If the charger safety relay is not enabled in software, then BMS does not latch the current limit to zero after a charge is completed. For this reason, in some applications such as solar, wind, and standby power, the charger safety relay may not be enabled to prevent the BMS from latching off.

By default, the charger safety output latches off until power is removed from the CHARGE pin on the BMS and is re-applied (for a vehicle application, this generally corresponds to someone unplugging the vehicle and plugging it in again the next time they wish to charge). This output can be configured to turn back on every so many minutes while the balancing algorithm is active or indefinitely even after balancing has finished. If the relay turns back on due to one of these settings, the charge current limit will be restored while the relay is back on and will latch to zero amps again when the BMS turns the charger off. The BMS will provide a diagnostic parameter in the live text data tab of the utility to indicate that the charge current limit is latched to zero because the charge is complete. This may be useful if attempting to determine if the BMS turned the charger off.

While the BMS can turn on the charger again to continue balancing if it is allowed to do so in the settings, the Orion Jr. 2 BMS switches off the charger completely when a cell reaches the maximum voltage and will continue to balance the pack after the charger has turned off. *It is essential that the Orion Jr. 2 BMS is able to completely turn off the charger when it calls for an end of charge by turning off the charger safety output. Failure to do this will result in damaged cells.* The charger should not in any situation ever be allowed to continue charging at any amperage after the BMS has turned the charger off. Keep in mind that, for some chargers, the status of the charger safety output is transmitted digitally to the charger. When digital communication is used, an analog backup method of shutting down the charger must be provided. This analog backup is in addition to programming the charger with a maximum pack voltage.

Charger safety flow chart



Watchdog Circuit

The four primary relay outputs on the BMS (Charge Enable, Discharge Enable, Charger Safety and Multi-Purpose Enable) are protected by a secondary monitoring circuit (called the watchdog). Specifically, the watchdog provides redundant monitoring of critical data (cell voltages and temperatures) to confirm that the main processor is interpreting data correctly. Additionally, the watchdog regularly issues rotating logical challenges to the main processor to verify proper operation.

If the watchdog detects an abnormal condition (one or more cell voltages out of range, one or more temperatures out of range or multiple challenge response failures from the main processor) it will override the main processor and shut off all four primary outputs (Charge Enable, Discharge Enable, Charger Safety and Multi-Purpose Enable) until the issue is resolved (relevant faults are cleared or the BMS is reset / power cycled). This allows the watchdog to override the main processor control of the relays and shut them down in a fault condition providing redundant safety functionality.

The watchdog circuit is operating continuously whenever the BMS is powered.

CANBUS Communication

The Orion Jr. BMS has an optional CAN (controller area network) interface. The interface has a programmable frequency (baud-rate). The BMS features up to 15 programmable CAN. These messages are designed to be flexible to interface with other electronic control units, computer systems, displays, or any number of different devices. Virtually all BMS parameters are able to be transmitted in these CAN messages. Please see the “Editing CAN Messages” section of the Software Utility manual for details on programming custom CAN messages.

In a CANBUS network there are always exactly two terminator resistors. It is up to the user to ensure that there is the proper number of terminator resistors on each CAN network. *By default, the Orion Jr. BMS has a terminator resistor already loaded on the CAN interface, but it can be special ordered without the termination resistor is needed.*

The CAN interface may also be used to upload settings. However, all BMS firmware updates must be performed using the RS-232 serial interface. Firmware updates may be necessary to add additional future functionality.

Cell Broadcast Option - The BMS can be configured to rapidly transmit cell voltages onto the CANBUS. This is useful when data logging as it is the fastest method for the BMS to transmit cell voltages.

Analog 5v Outputs

Three (3) analog 0-5v reference outputs are provided for the ability to set current limits for external loads or chargers as well as to provide an analog reference for state of charge and current going in or out of the battery pack. Analog voltages are not as precise as digital signals. Therefore, CAN communications are the preferred method of setting external current limits.

Two of the 5v outputs are dedicated to the charge and discharge limits respectively. The BMS will automatically output the discharge and charge limits on these 5v lines (with 0v being 0A and 5V being the maximum *analog* current limit set in the profile). If the application requires scaling the 5v output lines for any reason, there is a parameter in the battery profile (under the "Discharge Limits" and "Charge Limits" tabs) that allows the user to specify a different maximum analog output charge limit (and discharge limit). Note that the voltage range of these outputs is 0-5v, and the maximum range cannot be increased. If a 0-10v or other voltage range is needed, an external op-amp or other level shifting device must be used.

The other 5v analog output is for state of charge. The state of charge will vary between 0 and 5 volts representing 0% to 100% state of charge respectively.

How Balancing Works

The Orion Jr. 2 BMS takes an intelligent approach to balancing that seeks to maintain and improve balance from cycle to cycle.

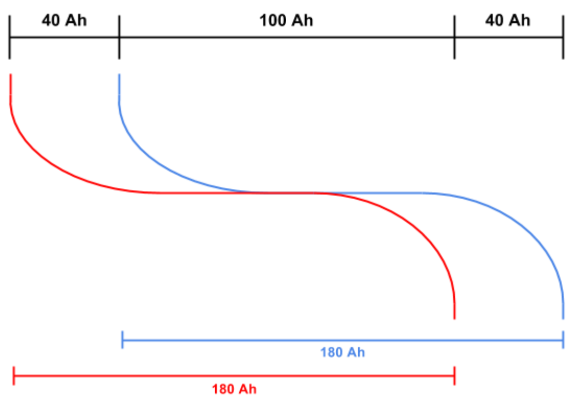
Lithium ion batteries, unlike lead-acid batteries, tend to stay in balance very well once initially balanced. Differences in self discharge rates, cell temperature and internal resistance are the primary causes of an unbalanced battery pack in a properly designed system, and these differences in self discharge rates are typically measured in micro amps (uA). The BMS must be able to add or subtract charge from the lowest or highest cells to compensate for the difference in discharge rates to keep the cells balanced.

The purpose of balancing a battery pack is to maximize the usable capacity. Even in the best battery pack, all cells will have slightly different capacities and will be at slightly different balances. The total usable capacity of the battery pack is limited to the lowest capacity cell, less the difference in balance from the strongest to weakest cell. While the proper solution for a low capacity or weak cell is to replace it, the BMS can balance and protect cells from damage from overvoltage and undervoltage no matter the state of balance or difference in capacity provided the BMS has been integrated with the application properly.

The Orion Jr. 2 BMS uses passive balancing to remove charge from the highest cells in order to maintain the balance of the pack. The passive shunt resistors dissipate up to approximately 150mA per cell. While that amount may seem small, that current is more than sufficient for maintaining balance in very large battery packs. Difference in cell internal self discharge rates are often measured in the tens to hundreds of uA (with a uA being 1/1000 of a mA.) Even with a very high difference in self discharge rate of 1mA, the 150mA balancing current is still 150 times that of the discharge rate. While every battery pack is different, for a 40 amp hour battery pack cycled once a day a typical maintenance balance completes in only about 20 minutes.

It should be noted that the balancing does not need to occur every cycle. Even if the battery has not had a maintenance balance in many cycles, the BMS will still protect the batteries. Except for the very extreme conditions, the majority of the battery pack capacity will remain usable even after many months without a balancing cycle. For example, a battery pack with 30Ah cells and a 1% SOC imbalance from highest to lowest cell (a fairly significant imbalance) the pack will theoretically have a usable capacity of 29.7Ah. Balancing the pack perfectly would only gain 300mAh of usable capacity in this case, which is fairly negligible, but can be easily reclaimed in around 2 hours by allowing the BMS to balance the batteries.

The Orion Jr. 2 BMS is not designed to do an initial balance on a battery pack that is more than about 10-15 amp hours out of balance. In those cases, the battery pack should be pre-balanced by either charging the cells to roughly the same SOC one by one or by charging / discharging the lowest and highest cells so that they are roughly at the same SOC. The image below is an example of two cells grossly out of balance with each other (40 amp hours out of balance.) Although this example pack is grossly out of balance, more than 50% of the capacity is still usable. For more information on pre-balancing, please see our application note on pre-balancing cells.



Balancing on the Orion Jr. 2 BMS only occurs when the BMS is powered in CHARGE mode (powered by CHARGE power on the Main I/O connector). When any one cell in the battery pack exceeds the “Start Balancing” voltage, the BMS will begin the balancing algorithm for all cells. The BMS will look for the lowest cell and then place a load on all cells which are more than the maximum difference in voltage above the lowest cell. For example, if a battery pack consists of 4 cells at 3.5, 3.51, 3.65 and 3.49 volts and the maximum difference in voltage is configured for 10mV (0.01 volts), the BMS would only apply a load to the cell which is 3.65v, to bring it down to within 10mV with the rest of the cells. This algorithm continues until all cells are balanced to within the pre-defined maximum difference in voltage and continues even after the BMS has switched off the charger. Once all cells are within this voltage, balancing will stop until power is removed and re-applied to the CHARGE power pin (pin 4) on the BMS (i.e. the next charge cycle).

The BMS has a safety feature to prevent over-discharging any cell during balancing in the event of a defective or dead cell. A minimum balancing voltage threshold allows the programmer to specify a voltage threshold at which the BMS is not allowed to remove energy from a cell. While the rest of the cells will continue to balance, the BMS will not place a load on any cell which is below this threshold, even if a cell below this threshold needs to be balanced. The purpose of this feature is to protect the cells from over-discharge and to prevent a possible race condition where the BMS removes charge from alternating cells. Balancing will be disabled completely if the BMS enters into a voltage failsafe mode such as if an open cell tap wire is detected.

The start balancing voltage setting should typically be configured to a voltage that indicates a cell is within approximately 5-10% of the maximum state of charge. For iron phosphate this is typically about 3.5v and varies with other chemistries. The maximum delta voltage (difference in voltage from the highest to lowest cell) recommended is 10mV for most lithium ion chemistries such as iron phosphate, but may be adjusted slightly lower for certain chemistries with a linear discharge curve (such as many manganese or polymer type cells.) A value too low will cause a race condition, reducing or eliminating the effectiveness of the balancing algorithm, and 10mV is recommended unless research has been done on a lower setting. When balancing a grossly out of balance pack, choosing a higher number such as 20mV may increase the speed of bulk balancing, but should then be reduced back to 10mV for finer balancing.

The minimum balancing voltage setting is simply to prevent cells from becoming over-discharged. This value can be set to a fairly low voltage, often a voltage corresponding to around 25% state of charge. For iron phosphate a voltage of 3.0 to 3.2v is appropriate. The minimum balancing voltage setting must be low enough to allow the BMS to effectively perform balancing and must be below the “settling” voltage.

When the BMS is balancing, the balancing will pause every so often to allow cell voltages to settle and to re-evaluate the balance of the cells in the pack. This is a normal part of the balancing algorithm and happens at set intervals. If the BMS unit itself is at an elevated temperature, the BMS will pause for a longer period of time to prevent overheating. To prevent a burn hazard, the BMS will not balance at all when the internal temperature is above 55C.Please note that, although the BMS has this overheating protection feature, the BMS unit must have sufficient ventilation at all time as it must be able to dissipate heat in certain abnormal operating faults.

While the BMS is most effective and is normally usually used to perform “top balancing” (synchronizing all cell voltages at full state of charge.), it is possible for the BMS to be used for “middle balancing” or “bottom balancing” by adjusting the balancing voltage thresholds and in some cases, by using an external controller to signal the BMS when to balance. Whenever possible, top balancing is strongly recommended, particularly for applications which are rarely at a low state of charge.

While the Orion Jr. BMS uses a different approach, some other battery management and charging systems on the market use “bypass” regulators, which turn on a battery charger to a predetermined amperage and then “regulate” the voltage of the cell by clamping the voltage and burning off the difference between the energy the charger is supplying and what the cell needs. While this approach works, it is typically inefficient, requires large bypass resistors, and actually unbalances the batteries before it can then re-balance them. The Orion Jr. BMS does not use this process and therefore does not require balancing circuits sizes as large. The Orion Jr. BMS switches off the charger completely when a cell reaches the maximum voltage and will continue to balance the pack after the charger has turned off. *It is essential that the Orion Jr. BMS be able to completely turn off the charger when it calls for an end of charge. Failure to do this will result in damaged cells and a potential fire hazard.* The charger should not in any situation ever be allowed to continue charging at any amperage after the BMS has turned the charger off.

The Orion Jr. 2 BMS can be configured to turn the charger back on at set intervals if necessary to continue the balancing process. This is configured in the settings for the charger safety relay settings. For certain chemistries it may be desirable to turn the charger back on every 30 minutes to an hour to aid in the balancing process. This is especially true for iron phosphate cells where the difference in state of charge is not evident unless the cell voltages are over approximately 3.4 volts. By turning the charger on every so often during the balancing process, the difference in voltage will become greater and allow for finer tuned balancing. The Orion Jr. 2 BMS has three options for turning the charger back on based on time alone: Disabled, every *n* number of minutes while balancing is still active, and every *n* number of minutes even after the battery is balanced. Turning the charger back on even after balancing has completed is intended only to be used for certain situations where the battery must constantly be topped off due to constant use and should not be used in normal circumstances.

In addition to the time based re-enable conditions, the BMS can also re-engage the charger if the state of charge drops below a programmed percent (also available on the charger safety relay settings tab).

Open Wire Fault Detection Circuit

The BMS has an integrated "open wire" detection circuit that is designed to identify situations where the physical wire connection between the cell itself and the BMS is compromised (whether it be loose, damaged, or disconnected entirely). This can take a number of different forms as the issue could be at the cell terminal (bad busbar, loose busbar, loose screw terminal, bad ring terminal crimp, etc), along the way to the BMS (smashed, sliced or internally frayed / damaged cell tap wire) or at the BMS itself (debris in the connector, damage to the connector itself OR if an internal fuse inside the BMS blows, severing the link between the BMS itself and the cell terminal entirely).

NOTE: It is possible in some circumstances for a cell voltage to appear relatively normal while at rest even with a severely compromised (or completely severed) voltage tap wire due to the way the BMS measures cells. Specifically, internal protection diodes inside the BMS have a very small leakage current (usually measured in nano-amps). This leakage current can cause a disconnected input to float causing the reading for the cell with the bad tap wire plus one adjacent cell to read incorrectly. When only a single cell tap wire is disconnected (on a cell other than the first or last in a group), the sum of the two voltage readings will be the sum of the two cell voltages, but each of the two adjacent cell voltage readings may be wrong. This may result in one cell voltage reading incorrectly high and an adjacent cell voltage reading incorrectly low due to the open wire. If the leakage current of two adjacent protection diodes is equal, the voltage may be approximately the expected voltage even though the BMS is not actually measuring a voltage. Due to this behavior, the open wire fault detection circuit is provided and cannot be disabled.

It is important to note that a wire may look perfectly fine on the outside, yet still have an internal break. Additionally, a ring terminal crimp may outwardly appear perfect yet still not be making good contact with the wire conductor.

In order to gauge the quality of the connection between the BMS and the cell itself, the BMS will very briefly apply a tiny load current (~100 micro-amps) to each of the cell taps and looks to see if there is any significant voltage drop due to this load. The BMS then very briefly applies a tiny charge current (again ~100 micro-amps) to each of the cell tap inputs and measures for a significant voltage rise. This effectively measures the resistance of the connection between the BMS and the cell. If the BMS sees *both* a significant drop when applying the load current *and* a significant rise when applying the charge current, the BMS will increment a counter indicating that the wire for that cell is open (compromised). If the BMS finds *three or more failures* within a rolling time-frame for the same cell, it will conclude that the wire is open and will set an open wire fault on that specific cell. This means that the likelihood of a false positive is statistically improbable, even in applications where the voltages are changing rapidly and unpredictably (high-frequency inverter applications, for example).

NOTE: The BMS does **NOT** transmit or use the voltages measured during when these tests are active. This means that the application will not see any voltage spikes or drops due to these tests under normal conditions (the BMS simply does not transmit or use the voltage data collected during these tests [instead relying on the data collected immediately before the tests], which last approximately 30ms once every 15 seconds).

The BMS continues to run these tests indefinitely whenever it is powered, so it is constantly monitoring for solid connections with the BMS.

If the open wire fault detection circuit does trigger and a formal fault code is set, the BMS will inhibit all charge and discharge operations until the fault code is addressed (cleared, or the BMS is power cycled / reset). This is done because if this fault triggers it means that the BMS does not have the ability to reliably measure all cells within the pack and therefore cannot guarantee that all cells are remaining within the required voltage ranges.

For more details on the Open Wiring fault and for instructions on how to resolve the issue, please see the Orion BMS troubleshooting guide entry for the **P0A04 Open Wiring Fault** code.

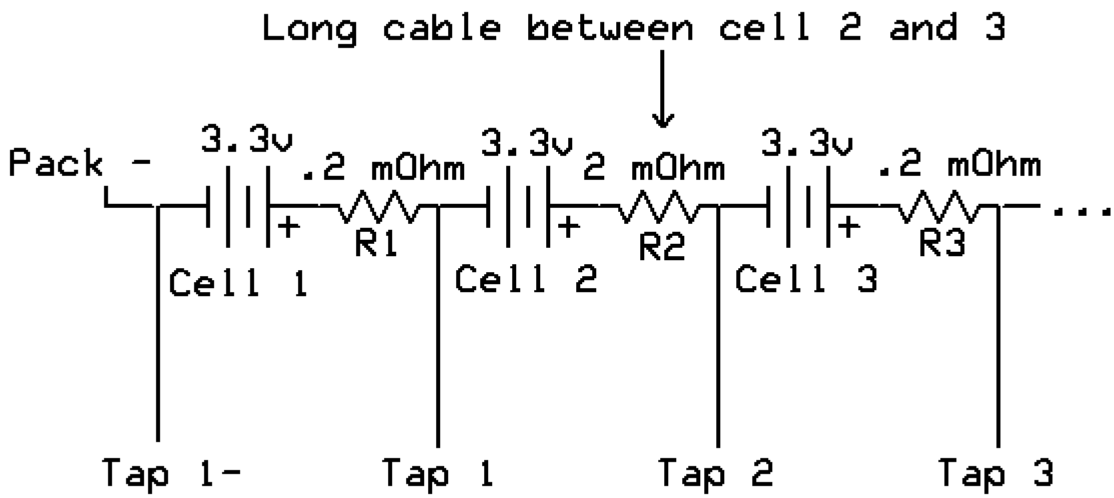
Busbar Compensation

Voltage measurements are taken by the Orion Jr. 2 BMS with respect to the next lowest cell or the negative wire in each cell group. For example, when the Orion Jr. 2 BMS measures cell 1's voltage, it measures the voltage between tap 1- and 1. Likewise, for cell 2, the voltage is measured between cell tap 1 and tap 2 to determine cell 2's voltage.

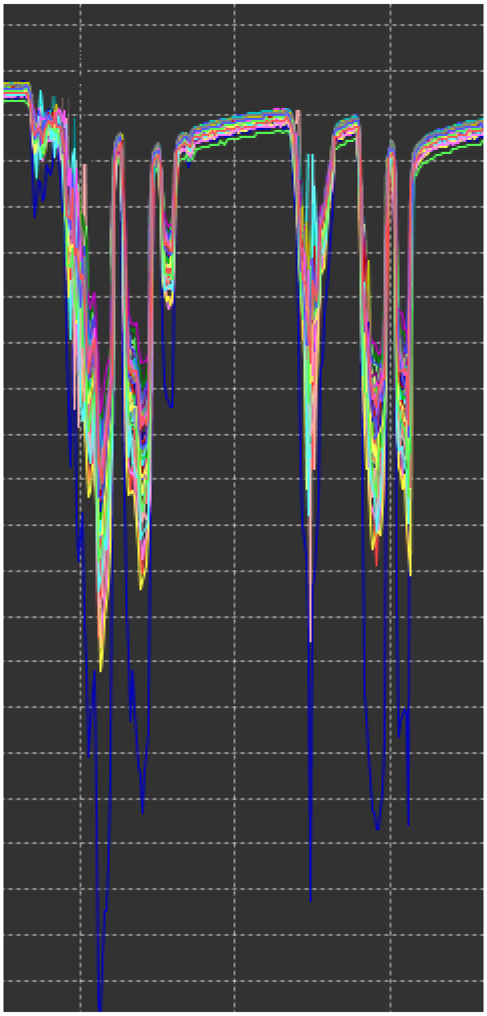
While battery cables and busbars may be very large and have a minimal resistance, all cables have some electrical resistance, and that resistance, while small, may influence the measured cell voltages while under load. The cell taps by necessity will see the additional resistance from busbars, battery interconnects, and cables unless they fall between cell groups (12 cells). The diagram below shows the first 3 cells wired in a group.

If cell voltages are measured by the Orion Jr. 2 BMS with no current flowing through the circuit, the voltages measured are exactly the voltage of the cells. When a current is running through the pack, the measured voltage of each cell will drop (or increase) due to the internal resistance of the cells, and the measured voltage (instantaneous voltage) and the open cell voltage of the cells will be different.

Because of the way the cells are connected, the differences in resistance from one interconnect to another will be reflected in the instantaneous voltage measurements and would show up to the Orion Jr. BMS as extra resistance for that particular cell. In the example below, all of the cells have a resistance of 3 mili-ohm, but due to the busbar resistances, the BMS sees the extra 2 mOhm resistance for a total of 5 mOhm on cell 2. Even though cell #2 is still healthy, it appears to be a weak cell due to the resistance of the long cable. This is where busbar compensation comes in.



For relatively lower resistance, this extra resistance can be compensated out by the BMS using "busbar compensation" (see the software manual for information on setting up busbar compensation). For high resistance busbars / cables (or higher amperage applications), it is possible for the voltage drop (or voltage increase if the battery is being charged) to be large enough that it can cause the voltage at the tap to exceed 5V or drop below 0V (which are the maximum and minimum voltages for the Orion Jr. BMS.) If the voltage can swing outside those maximum voltages, the Orion Jr. 2 BMS must be wired such that the cable falls between the cell group break (between cell 8 and 9) such that voltage drop induced by the busbar cannot be seen by the Orion Jr. 2 BMS. Whenever possible, it is best to wire the cell taps such that the BMS cannot see the extra resistance.



Voltage drop under load from an uncompensated high impedance busbar causing additional voltage drop (blue line)

The BMS allows busbar compensation to be added to specific cells in the cell population table. The compensation must be applied to the cell where the extra resistance shows up. This depends on the physical placement of the cell tap wires as the tap could be placed before or after the long cable.

The amount of busbar compensation is sometimes difficult to get correct on the first try. While it is possible to calculate the theoretical resistance of the wire based on the gauge and length of the cable, it is often difficult to calculate any extra resistance from crimp connectors and terminals. It may be necessary to measure the actual resistance using ohm's law to look at voltage drop under load across the cable or by trial and error charting all cell voltages.

Busbar compensation generally should only be used for long cables. While the BMS has this feature, it is always better to wire the battery pack such that high resistance busbars and cables fall between cell groups instead as this will produce more reliable results. This is especially true for applications with rapidly changing currents or applications which may have some skin effect or large amounts of EMF present.

Thermal Management and Fan Controller

The Orion Jr. 2 BMS measures the battery temperature through 3 main thermistors connected directly to the BMS with the option of additional thermistors through a thermistor expansion module (sold separately). The BMS calculates the minimum, maximum, and average temperatures of the battery pack based on the attached thermistors. These temperature readings are used in the calculation of maximum possible charge and discharge current limits, which are used to determine when and at what amperage a battery pack can be charged or discharged.

The multi-purpose outputs may be programmed to turn on or off at specific temperature, which may be useful in some applications. Please see the “Multi-Purpose Output” function for more information on that feature.

For more information about the hardware interface for the fan controller, please see the wiring manual.

Multi-Purpose Input

The BMS has one multi-purpose input pin which can be used to trigger a few different functions on the BMS. The function of this input pin is defined in the BMS settings (under the General Settings tab). The functions available are:

1. ***Clear all error codes*** - when the BMS is configured with this option, all fault codes will be cleared in the event that the BMS senses this output turn on (note: a fault code may re-occur immediately if there is an active fault condition). Note that clearing all fault codes will erase data that may be necessary for a technician to diagnose a potential issue. This option generally should not be provided end users as end users tend to clear codes without diagnosing the root issues, which may indicate dangerous situations.

2. ***Ready status*** – when this option is selected, the status of this pin is monitored to tell the BMS if the READY power source is present on the BMS. This option can be used to prohibit discharge unless power is present on this pin.

3. **Alternate Charge Current Limit** - This feature will change the maximum possible charge current limit to a lower value only when the BMS detects this input is energized (the alternate value can only lower the maximum charge current limit). This feature may be useful when the user needs to select between two different charging speeds such as a standard charge or a fast charge.

4. **Alternate Minimum Cell Voltage** - When this function is selected the BMS will use the Alternate Minimum Cell Voltage value (specified in the utility) for the minimum allowable cell voltage when the Multi-Purpose Input signal is INACTIVE (off). The Alternate Minimum Cell Voltage value must be higher than the actual Minimum Cell Voltage value programmed into the BMS. Once the Multi-Purpose Input signal is raised high (ON) then the BMS will revert to enforcing the actual Minimum Cell Voltage value. This can be useful if the operator wants to momentarily allow the pack to be discharged further than normal under certain circumstances.

5. **Charger Plugged In Status** - This allows one of the multi-purpose inputs to be used to indicate whether an AC mains charger is plugged in for enabling the Charge Interlock failsafe condition (to help prevent driving away with a vehicle still plugged in). Typically, this is accomplished by

the Charge Power input being energized (Main I/O harness pin 4) however in some situations this may not be possible and so this input function allows for an alternate method to do so.

Multi-Purpose Output

The BMS has one multi-purpose output. This open drain output can sink 175mA and is active low (pulls to ground) when on. The output can be used to drive a relay or other device, and the status of this output can be transmitted digitally if needed via the CANBUS (with the CAN enabled software). The function of this is set in the BMS profile on the General Settings tab. Available functions:

1. **Error Signal Output (default)** - In the event that any fault codes are present on the BMS or in the event that both CHARGE and READY power are present to the BMS at the same time (if this behavior is enabled), this output will turn on. It can be used to drive an LED, buzzer or other device (additional components may be required, see the wiring manual for details). The basic analog display module makes use of this multi-purpose output function.

2. ***CANBUS Controlled output*** - When this option is selected, the status of this output is controlled by a CANBUS message. For example, when a particular byte on a CANBUS message is 1, this output would turn on. Note: Additional CANBUS configuration is required to specify the ID and byte of the message which will turn this output on. This should not be relied on for safety operations such as enabling charge or discharge.

3. ***Low SOC output*** - This output will turn on whenever the state of charge drops below the predefined SOC threshold. This output will turn back off once the calculated state of charge rises above the predefined turn-off condition. The difference between the turn on and turn off values provide hysteresis to prevent rapid oscillations.

4. ***Temperature Output*** - This feature allows the operator to specify whether the output will turn on when a temperature is too low OR too high (and to specify the temperature to turn back off at). By default, this is configured to activate for low temperatures, but the polarity can be switched (via the Output Polarity checkbox) to make it activate for high temperatures. The temperature is derived from any of the 3 integrated thermistors or from any attached external thermistor expansion modules. When configured for low temperature activation the BMS will use the absolute lowest temperature from all available sensors. Likewise, when configured for high temperature operation it will select the absolute highest temperature from all available sensors. The difference between the turn off and turn on values provides hysteresis to prevent oscillations.

5. ***Charge Interlock Output -*** This option will cause the multipurpose output to turn on if the BMS detects both CHARGE and READY power sources at the same time. While powering CHARGE and READY power at the same time poses no problem for the BMS, sometimes it is desirable to inhibit driving via an external means or illuminate an LED when this happens. **NOTE: Requires MPI to be assigned as READY POWER status function** (otherwise the BMS will not be aware of the Ready Power input status).

6. ***High Cell Voltage Output*** - This option will cause the output to turn on if the highest cell in the pack reaches the high cell voltage threshold. The output will turn off when all cells have fallen back down below the turn off value. The difference between the turn on and turn off voltages provides hysteresis to prevent oscillations. **NOTE:** **This output is not designed to be the primary control for discharge or charge**. Use the charge enable, discharge enable, charger safety or CANBUS for primary control of charge and discharge.

7. ***Low Cell Voltage Output*** - This option will turn the multipurpose output on if the lowest cell in the pack drops below the threshold. The output will turn off when all cells have risen above the

hysteresis threshold. Note: This output is not designed to be the primary control for discharge or charge. **NOTE: This output is not designed to be the primary control for discharge or charge.** Use the charge enable, discharge enable, charger safety or CANBUS for primary control of charge and discharge.

8. ***Low DCL Output*** - This option will cause the multipurpose output to turn on in the event that the calculated discharge current limit from the BMS falls below the threshold. The output will turn off when it rises again above the pre-defined amount.

9. ***Low CCL Output*** - This option will turn the multipurpose output on in the event that the calculated charge current limit from the BMS falls below the threshold. The output will turn off when it rises again above the pre-defined amount.

10. ***Contact Enable Output*** – The line is active as long as there are no critical fault codes present. Critical fault codes are defined by the following: **P0A06 / P0A07** (a charge / discharge enforcement fault is detected), **P0AC0** (a problem with the current sensor is detected), and **P0A04 / P0AFA / P0A01 / P0A03** (a critical voltage sensing fault is detected). The output will re-engage once these fault codes are cleared. Other non-critical faults (such as thermistor fault, etc.) will NOT cause this output to turn off. Additional criteria can be specified to turn off the output. These criteria include maximum / minimum pack temperature and maximum / minimum cell voltage. **NOTE: Once the contactor enable output turns off it will remain off until the unit is power cycled.** The maximum / minimum cell voltage limits that are specified for the Contactor Enable Output will not trigger unless they are exceeded for 10 seconds or more, so if the minimum cell voltage for the contactor enable output is set to 2.8v the output will not turn off until the lowest cell voltage is less than 2.8v for more than 10 seconds.

11. **Output Function Disabled** – This option disables the output if it is not being used.

12. **Idle Timeout** - When in this mode, the output will remain active (ON) as long as the BMS detects at least a certain amount of current activity within the battery pack (**EITHER** charging **OR** discharging). The timeout period (in minutes) and the idle amps threshold (in amps) are both programmable. This output can be used to open a relay cutting power from the battery to preserve battery power.

Collected Statistics (Cell Warranty Data)

Usage statistics are collected from the battery pack and stored by the BMS in long term memory. These statistics are stored in non-volatile memory on the BMS. Data collected is intended to be used to track the number of events that occur including over-voltage, under-voltage, time spent above and below certain temperatures, and the number of events that occur. Collected cell data can be reset through the BMS utility, but total runtime, total power-ups and total profile updates cannot be reset by any means.

Parameters tracked include:

1. **Total runtime** - the total amount of time the BMS is active, stored in minutes.
2. **Total power-ups** - the number of times that the BMS unit has been powered on.
3. **Total profile updates** - the number of times that a BMS profile has been updated on the BMS.
4. **Total pack cycles** - the cumulative number of cycles placed on the battery pack. One cycle is calculated by summing the current in and out of the pack and dividing by the amp hour capacity of the pack. For example, if a battery pack is charged 50 amp hours and discharged 50 amp hours and it is a 100 amp hour pack, the BMS records this as a half of a cycle.

5. **Total time above 45C, 60C and below -20C**. These three parameters store the cumulative time that the BMS was powered and the battery pack was measured exceeding any of those temperatures. This is useful for battery warranty information as cell lifespan can be significantly reduced due to elevated temperature. Events are only recorded if they last more than one second and are not recorded if all thermistors are in an active fault state.
6. **Total time over and under-voltage.** These two parameters record the total amount of time that a cell's voltage was above or below the maximum or minimum cell voltage respectively while the BMS was powered. This information is useful for cell warranty as it can be used to show if a cell was damaged due to over or under voltage. Time is only accrued if the cell voltage event lasts more than one second.
7. **Total over and under-voltage events**. These 2 parameters show the number of times that a cell's voltage has exceeded the maximum voltage or dropped below the minimum cell voltage for one second or longer. The number of events can be used to help determine if a cell was regularly overcharged or over-discharged.
8. **Total charge and discharge enforcement events.** These 2 parameters record the number of times the BMS turns off either charge enable or discharge enable outputs but the BMS continues to sense charge or discharge currents into our out of the pack. Events are not recorded if a current sensor fault is present.

Histogram data indicating the amount of time that a battery pack has spent at various stages of charge, various temperature, and various C rates (a C rate is amperage divided by the amp hour capacity of the cell). The data is collected only while the Orion Jr. 2 BMS is powered up.

The Orion Jr. 2 BMS also maintains an event log. Events include outputs turning on and off, state of charge drifts, charge completion, and other related events. This log is intended to be used to aide in diagnosing intermittent issues or events that happen only at certain points in time.

Failure Mitigation

The Orion Jr. 2 BMS features several failsafe modes to protect the battery pack should something go wrong with the BMS unit or attached wiring. Although these internal redundancies and protection procedures are provided, it is the responsibility of the user to ensure that the BMS is configured, connected, and used in a manner in which failures are properly mitigated and handled.

For any application where a battery pack is used, the user must think through all possible failures, provide redundant systems, and determine that each failure mode is safe and acceptable. Generally speaking the worst case situations are situations where a failure can occur, and the application is not aware that the failure has occurred and therefore runs using incorrect data. Because the requirements vary from application to application, it is the responsibility of the user to determine acceptable risk and design the rest of the system to mitigate risks.

Any application should be setup such that a disconnected or loose wire should cause a safe failure (that is to say, if a failure occurs it should not be able to damage the battery or other parts of the application). For this reason, the BMS's digital on/off outputs are setup to be active low to *enable* charge or discharge. While the settings for when to enable charge and discharge can be changed, the polarity of the enable digital output cannot be changed for the purpose of preventing accidental incorrect configuration of the polarity.

Although the following is not an exhaustive list, here are common failures to consider:

1. ***Loose / disconnected wire on cell voltage tap or failure of a cell voltage sensor*** - This is a major issue for any BMS system since the BMS cannot measure cell voltages for cells that it is not connected to. The Orion Jr. BMS provides several lines of defense against open wires.

   If a cell tap wire becomes disconnected or intermittently disconnected (loose connection), the BMS features open wire detection where a small current is applied to the cell through the tap wire every so often to ensure that the connection is good. If the BMS detects that a wire has become loose, disconnected, or has sufficiently high impedance, it will set an open wire fault for the specific cell tap affected and go into a fail safe mode. If a wire which is not being used as a cell tap (for example if a cell group only has 6 cells connected, wires 7 and 8 in that case would not be actively being used) comes loose or disconnected, it may cause voltage reading inaccuracies that the BMS cannot detect. For this reason (and for improving accuracy of voltage readings in general), 2 or more wires should be used to connect unused taps to the cells as described in the wiring manual. Additionally, the BMS features internal self checking of the cell voltage sensors to detect errors with the sensors themselves as well.

   It should be noted that the BMS contains internal non-user serviceable fuses on cell voltage tap connections. When a fuse is blown (usually due to reverse polarity, over-voltage, or improper location of a safety disconnect / fuse causing current to flow through the BMS), the BMS normally detects a blown fuse as an open wire. Even though the wiring harness may be fine, the BMS may have internal damage leading to an open wire fault.

If a cell voltage tap wire becomes physically loose and makes contact with another cell at a different potential (either more positive than 5v or negative with respect to the potential it is supposed to be connected to), it will likely cause damage and the BMS will likely need to be serviced.

2. ***Improper software setup of the BMS resulting in not all cells being monitored*** - While this is not a condition that would be expected in a production environment, if the BMS is not setup to monitor all cells, it cannot protect the battery pack correctly. For this case, the BMS features a total pack voltage sensor which can be constantly compared to the sum of all cell voltages to look for inconsistencies. If inconsistencies are detected, the BMS will set a fault code and go into a voltage fail safe mode (described later). The variance allowed is a user specifiable feature in the profile and can be disabled if used in a production environment where this feature is not necessary. The total pack voltage sensor is only accurate to within about 5% and may not always catch a single unpopulated cell, particularly if cell voltages are fairly low or if the maximum allowable variance is set high.

3. ***Loose / disconnected wire on pack voltage tap or internal voltage sensor fault*** - Generally speaking, a loose or disconnected wire on the total pack voltage tap or a failure of the voltage sensor will cause a noticeable error in the total pack voltage sensor. As such, if the total pack voltage sensor is enabled and is reading 0 volts or if the reading varies significantly from the summed up cell voltages, an error code is set, and the BMS will go into a voltage fail safe mode unless the sensor is disabled since it cannot trust the voltage readings which are a critical part of the BMS's data collection system.

4. ***Loose / disconnected wire or failure of current sensor system*** **–** The Orion Jr. 2 BMS will enter into a current sensor fault if the actual current measured is greater than +/- 120% of the maximum rating of the current sensor. A current sensor fault will result in the BMS entering into a current sensor failsafe mode.

   The worst case scenario is if the current sensor malfunctions in a manner where values appear to be consistent but are incorrect, and the BMS cannot detect a failure. Such a failure could result from a high impedance or partially disconnected wire between the BMS and the current sensor or an incorrectly sized current sensor being used or selected in the BMS configuration. If a current sensor fault occurs, the BMS will continue to protect cells based on maximum and minimum cell voltages, but calculations based on current sensor values such as internal resistance, open cell voltages, state of charge, busbar compensation, and charge and discharge current limit values may become inaccurate. If additional redundancy is necessary for an application, an approach for increasing redundancy is to compare currents measured by the BMS with currents measured elsewhere such as at an inverter, load, or source. It should be noted that with a malfunctioning a current sensor, the BMS can still provide basic protection of the cells from over voltage and under voltage. As such, this failure mode will not cause the BMS it disable charge or discharge (although other related faults may).

5. ***Disconnected wire or failure of thermistor*** - A disconnected thermistor will result in an error code by the BMS and the BMS will ignore that specific thermistor until the error code is cleared or the BMS power is reset. The BMS determines a faulty thermistor if the measured value is

less than -40C or greater than +80C (a shorted or disconnected thermistor will read +81C or -41C.) In the event that a thermistor fault occurs, the BMS will disregard that particular thermistor. A thermistor failure (such as the use of an incorrect type of thermistor) may result in an inaccurate temperature reading, which may result in current limits being imposed on the battery pack incorrectly. Thermistor measurements can be viewed in the BMS utility to help locate thermistor failures.

6. ***Loose / disconnected wire on main I/O connector or loss of all power*** - The main I/O connector contains wiring for the CAN interface (for CAN enabled units), 5v analog interfaces, power and charge, discharge, multi-purpose input, multi-purpose outputs, and charger safety digital on/off outputs. Loss of both the READY and CHARGE power will cause the BMS to lose power and turn off.

   In the event the 5V analog voltage references are disconnected, the application must be setup in such a way the application goes into a safe failure mode. This is particularly true of the state of charge and amperage outputs since a disconnected wire could result in the application believing that the state of charge has dropped to an undefined floating value (if no pulldown is used) or 0% and the amperage has gone to the maximum value (or an undefined value if no pulldown is present).

   Digital on/off outputs are set up such that they are “on” (active low) only when they are enabled, so that a disconnected or loose wire will cause them to fail in an off condition and by default not allow charging or discharging.

   The multi-purpose input and outputs on the BMS must also be setup such that a failure or disconnection of one of the wires would leave the application in a safe state.

7. ***CANBUS communication failure*** - While CANBUS is a very robust protocol, systems should always be designed to tolerate a total or partial CAN communication failure. CAN buses may become unreliable if another node on the bus starts transmitting and clogs the bus, causing intermittent messages to get through, creates errors on the bus blocking all communications, or starts transmitting gibberish on the bus. Even though CANBUS is an incredibly robust protocol it is still vulnerable to some degree to interference or distortion. Because of this, there are 3 things should always be done when communications are necessary to prevent major failures:

   1. CAN systems should always be backed up with an analog system if the failure would be catastrophic if communication is lost or garbled. Analog backups are strongly recommended for all CANBUS controlled devices. If a charger is controlled via CANBUS, an analog backup must be used (the charger safety output is designed to be used for this).
   2. Any critical CAN system should always verify checksums at the end of the message before accepting data from that message. If a node on the bus is garbling messages or if electrical noise enters the CAN wires, messages can become distorted and bits may be incorrectly received.
   3. Any system that accepts CAN messages should feature a timeout such that, if a handful of messages are missed, the device should not trust the last known data but

rather go into a failsafe mode where it operates under the assumption that values are unknown.

8. ***Digital on/off safety relay failures*** - The digital on/off outputs are designed to be a last line of defense. However, they are often connected directly or indirectly to external relays which can fail. Ewert Energy strongly recommends providing at least 2 redundant methods for disabling charge, discharge, or any external battery charger since the BMS is unable to force a relay to turn off if it has failed. After the Orion Jr. 2 BMS attempts to turn off one of the relays (charge enable, discharge enable, or charge safety), it will continue to monitor to ensure that current flow has stopped. If current flow has not stopped within a pre-defined amount of time, the BMS will go into a relay failsafe condition where all digital on/off outputs are set to zero in an attempt to protect the batteries (mostly helpful in the event where a relay is wired to the wrong digital on/off output). Ultimately it is the user's responsibility to ensure that the application respects the BMS's command.

   The digital on/off safety lines are all configured as open drain outputs where they will float when off and will be pulled down to ground when enabled. It is important to note that if voltages exceed 70V on any of the digital on/off relay outputs, protection diodes inside the BMS will cause current to flow and will result in the output appearing to turn on. It is therefore imperative to ensure that the operating voltage never exceeds 70V, even briefly. Note that although the damage voltage for these pins exceeds 60V, the maximum allowable working voltage between any 2 pins on the BMS is 60V, and the voltage on these pins may not exceed 60V at any time.

   When the BMS is controlling a battery charger, the charger should be configured with a maximum voltage that will shut down the charger if the voltage of the pack ever exceeds the maximum possible voltage. This functions as a backup to prevent thermal runaway in the event that the BMS is unable to turn off the charger for whatever reason. Likewise loads such as motor controllers should be configured for a minimum voltage at which they will shut off as a redundant safety whenever possible. These should only be used as redundant backups and never relied upon for normal operation as a single cell may become too high or too low and will not be noticeable when only looking at the pack voltage.

9. ***Failure, shorting or disconnection of analog 5V output*** - If the 5V analog outputs are used to control applications, proper failure mitigation must be designed such that if the 5V analog wires become disconnected or shorted to 0V that the failure will be safe. Additionally, if overvoltage or reverse voltage is applied to the pins on the BMS, and internal damage occurs, resulting in inaccurate output voltages, the application should have a failsafe allowing the BMS to shutdown operation in a safe manner. *Note: The analog 0-5v outputs must always be used in conjunction with the charger enable, discharge enable, or charger safety outputs when used to control charge or discharge amperage!*

Understanding Failure Modes

The Orion Jr. 2 BMS has several failsafe software modes to ensure that the batteries are protected against internal and some external failures of the BMS. These modes are designed to place the priority on protecting the battery.

1. ***Voltage failsafe (non-operating)*** - This is the most serious failure mode and is triggered when the BMS has determined that it no longer has accurate cell or total pack voltages. This can be caused by an open (disconnected) tap wire, any populated cell which is reading a voltage below 0.09 volts, total pack voltage sensor reading 0 volts, or a discrepancy between the total pack voltage sensor and the sum of all the cell voltage sensors.

   Because the BMS cannot protect the cells if the accuracy of the cell voltages or the total pack voltages is compromised, the BMS is forced to enter into a non-operating failsafe mode. When the BMS enters into this voltage failsafe condition, the BMS will begin to gradually de-rate the charge and discharge current limits from their last known value down to 0 to prevent charging and discharging. The amount of time to de-rate the limits is specified in the profile and is designed to provide some usable time of the battery after the failure has occurred. The gradual current limit reductions are intended to alert the operator to the fact there is a problem while providing enough power to allow the application to come to a safe stop. This is particularly useful if the application is a light mobile vehicle or application where having some available power for a short period of time may be useful. This error condition should always be investigated prior to clearing the code.

2. ***Current sensor failsafe mode (degraded operation)*** - This failsafe mode is triggered when the BMS determines that the current sensor is either unplugged or has otherwise become inaccurate and cannot be trusted <u>*or if the BMS is configured for no current sensor*</u>. In this mode, the current sensor is disabled and will measure 0 amps. The BMS will continue to operate and protect the batteries purely using voltage based conditions. However, all functions relying on the current sensor are disabled. Care should be taken to correct this issue as quickly as possible, but it is possible to continue using the battery pack in this failsafe condition.

   The behaviors altered while in this failsafe mode:
   - Internal resistance calculations disabled (both cell and total pack)
   - Open cell voltage calculations disabled for both pack and individual cell calculations. The open cell voltages will read the same as the instantaneous voltage readings. This results in highly inaccurate state of charge drifts.
   - State of charge. This cannot be accurately calculated and will be guessed purely on voltage and based on drift points. Drift points are based on open cell voltages, so SOC will vary considerably and should not be trusted to be totally accurate.
   - Charge and discharge current limits switch to a voltage failsafe calculation mode and may be higher or lower than they should be. However, they will rapidly adjust if voltages approach minimum or maximum levels.
   - Cell protection based exclusively on cell voltages which may not provide full over-current protection.
   - *The BMS cannot enforce over current limit protections since current is unknown.*
   - *Busbar Compensation will effectively be disabled.*

3. ***Internal memory failsafe (non-operating mode)*** - In the event of an internal BMS memory failure (i.e. if the memory that stores the profile is damaged), the BMS will load the factory default battery profile with all outputs and inputs disabled to protect the battery. A diagnostic trouble code will be set to indicate this problem has occurred.

Diagnostic Trouble Codes

For the most up-to-date information regarding the available diagnostic trouble codes, as well as for instructions on how best to troubleshoot them, please visit the Troubleshooting section of the Orion BMS main website available below.

Troubleshooting Guide Link:
http://www.orionbms.com/troubleshooting