www.orionbms.com

Strings, Parallel Cells, and Parallel Strings

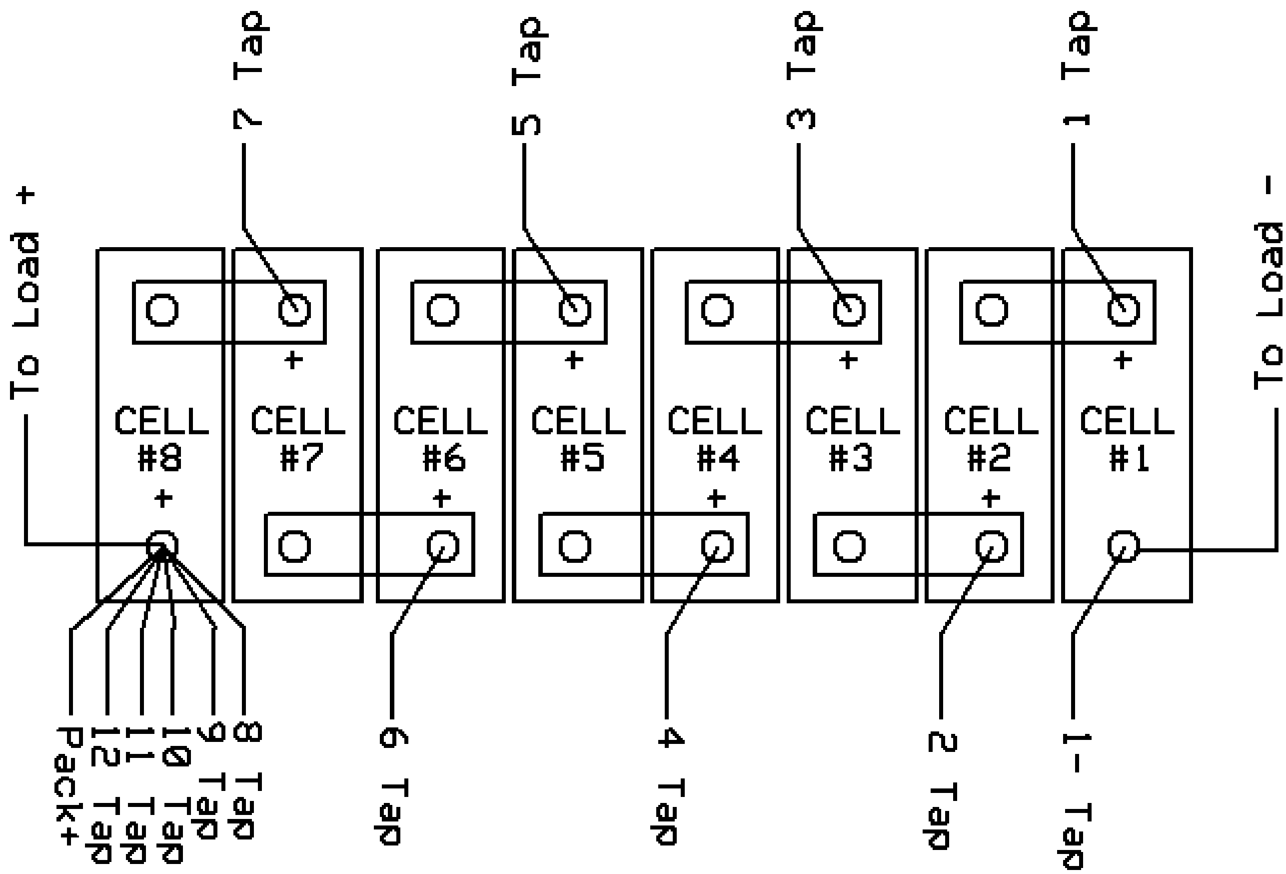
Whenever possible, using a single string of lithium cells is usually the preferred configuration for a lithium ion battery pack as it is the lowest cost and simplest. However, sometimes it may be necessary to use multiple strings of cells. Here are a few reasons that parallel strings may be necessary:

1. Redundancy (only for specific applications)
2. Hot swap capability (UPS applications, telcom, scalable systems, etc.)
3. When you must use a particular type of cell which is only available in a module with several cells in a string with no means of directly paralleling the cells.

Important Note: Due to the risks of parallel strings, additional external safety systems must be used in conjunction with the BMS when the Orion BMS or Orion Jr. BMS are used with parallel strings. Electrical engineering is required to use the Orion BMS or Orion Jr. BMS with parallel strings, and this work must be performed by an electrical engineer who is trained in working with and understands the risks of paralleled lithium ion batteries. Do not attempt to use parallel strings without proper training.

Standard Battery Configuration

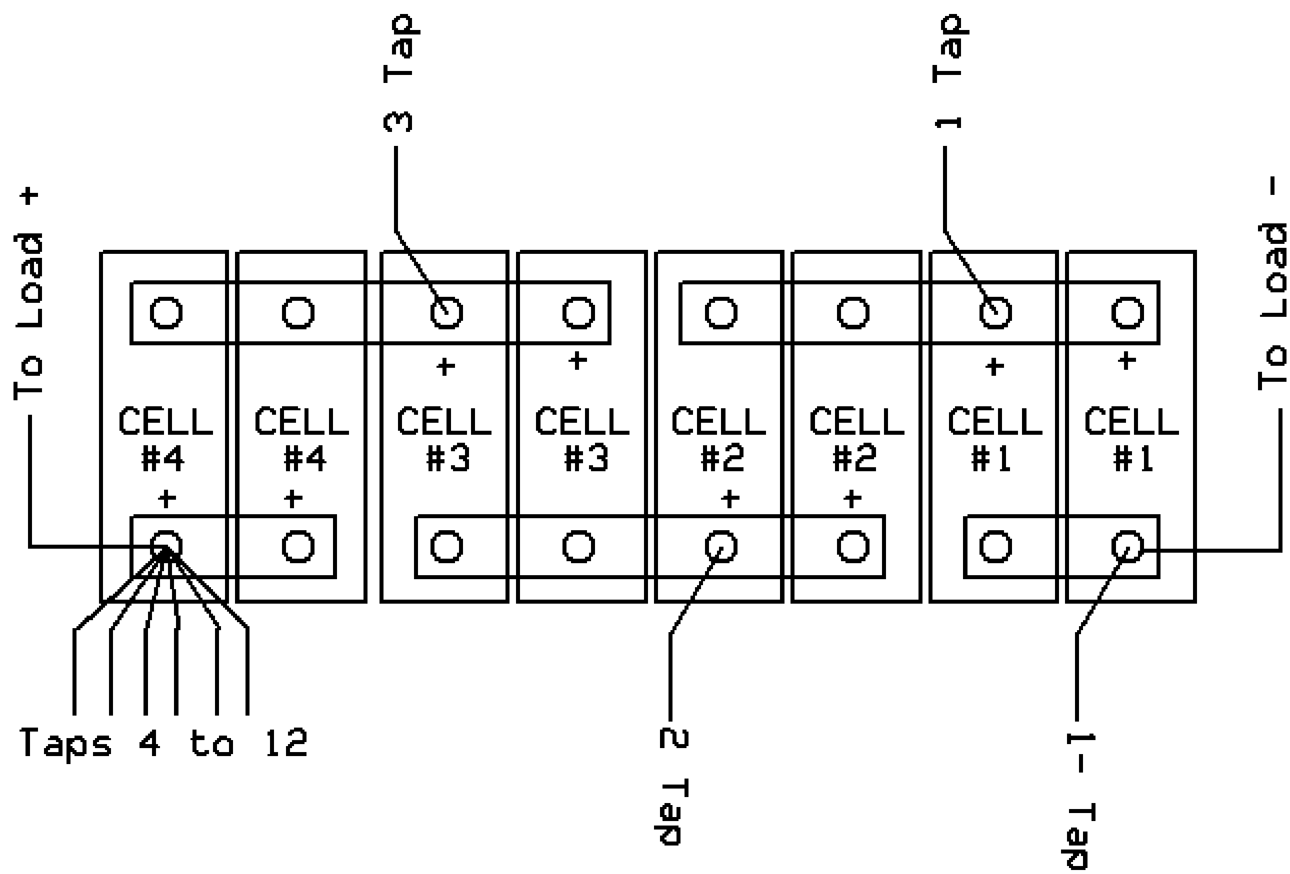
Below is a diagram of a standard 8 cell lithium ion string. Unless there are specific reasons for doing otherwise, this is the most desirable and simplest configuration:



In the above example, 8 cells are configured in a single string. This is an “8S1P” configuration. The “8S” indicates that there are 8 cells in series and the “1P” indicates that there are no paralleled cells. If each cell is 10 amp hours and 3.3 volts, the battery pack above would be 10 amp hours and 26.4 volts (3.3 volts x 8 cells). For this setup, a BMS capable of monitoring 8 cells in series is necessary.

Standard Paralleled Cell Configuration

Lithium cells can almost always be paralleled directly together to essentially create a larger cell. This is useful when a cell manufacture does not manufacture the correct size cell needed or when there are certain physical constraints. In some cases paralleling multiple smaller cells can also reduce the overall internal resistance and increase the power capabilities of the pack. The method of paralleling cells directly together as shown in the diagram below is generally the simplest and most preferred method of increasing the capacity of the battery pack.



In the above configuration, the amp hour capacity is increased without increasing the pack voltage. Even though 8 cells are used, because each cell is paralleled with one other cell, the BMS can treat each pair of cells as a single cell. This allows the designer to use a smaller BMS. The above configuration is a “4S2P” configuration. The “2P” indicates that there are 2 cells paralleled together, where-as the “4S” indicates that there are 4 of these pairs in series. If each cell is 10 amp hours and 3.3v, the battery pack above would be 20 amp hours (10 amp hours x 2 cells) and 13.2 volts (3.3 volts x 4 pairs).

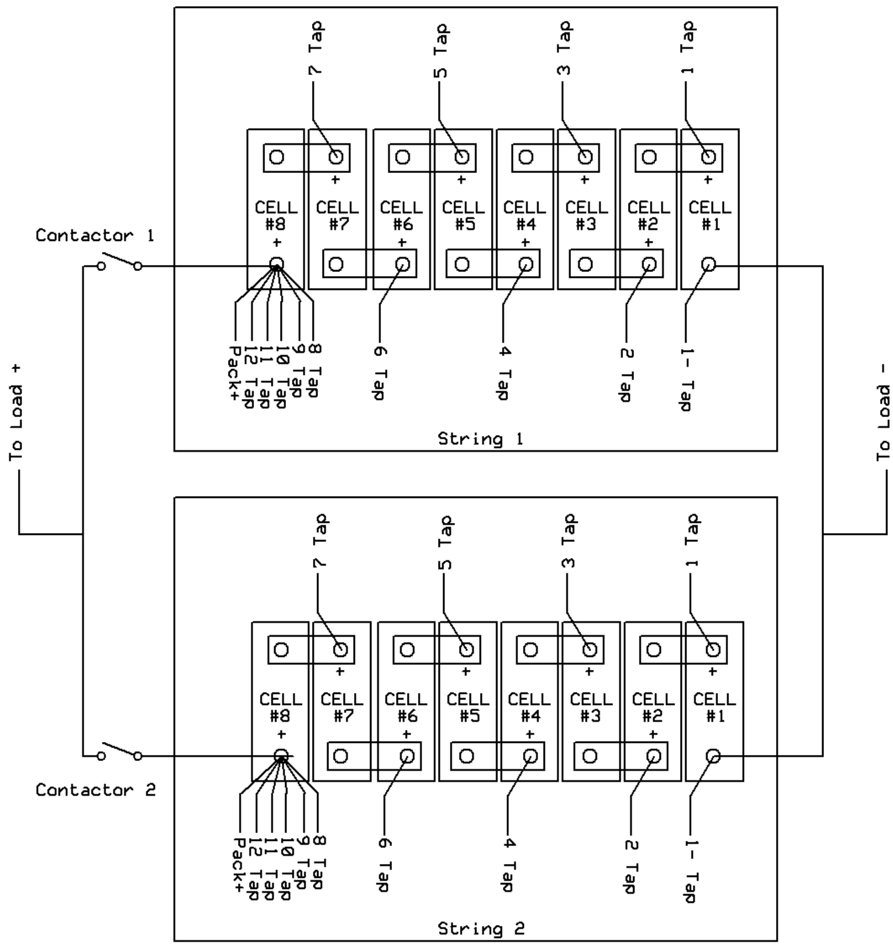
Even though there are twice the number of cells in this configuration, for this setup, a BMS capable of monitoring only 4 cells is necessary. In the case of cells which are parallel together and then assembled into a single string, as shown above, the BMS will “see” the two paralleled cells as a sing cell with twice the capacity and half the internal resistance of a single cell. Since there is a busbar between the two positive and two negative terminals of the batteries, the voltage of both cells is forced to be equal.

Therefore, monitoring the voltage of either cell will show the same results (less the very negligible difference in voltage caused by voltage drop on the busbar). In the event that one of the cells develops a reduced capacity or high resistance (as is typical for aged or failed cells), the stronger cell will take more of the load and essentially prop up the weaker cell. In that event, the BMS is able to see a decrease in the overall capacity or an overall increase in resistance. With two cells paralleled together, a single weak cell can affect the resistance up to 50% and the capacity up to 50%. If three cells are paralleled, a single bad cell can affect the resistance and capacity of the total paralleled block up to 33% (with four cells paralleled, up to 25%, and so forth). As more cells are paralleled, a single failure becomes more difficult to detect, but redundancy is also increased since a single cell failure will have less of an impact on the overall performance of the battery. Cells directly paralleled with each other will automatically balance each other since they are permanently connected.

Note: While most lithium batteries can be directly paralleled together, check with the cell manufacturer to ensure that the cells can be safely paralleled and to see if there are any specific requirements for the specific cells used. In some cases (such as with some 18650 style cells), cell manufacturers may require individual fuses or fusible link wire to prevent over current through a single cell in the event of a cell failure or an internal short within a cell. Consult with the cell manufacturer to determine if such a design is necessary.

Paralleled String Configuration

Paralleling strings together greatly increases the complexity of managing the battery pack and should be avoided unless there is a specific reason to use this configuration. In this setup, each string must essentially be treated as its own battery pack for a variety of reasons. In a below example, 2 strings of 8 cells each are placed in parallel.



In the above configuration, two "8S1P" strings are paralleled together. With perfectly matched and perfectly balanced 10 amp hour, 3.3 volt cells, the above configuration would have a total of 20 amp hours and 26.4 volts. However, in reality, the total usable capacity of this pack will be less than 20 amp hours. Additionally, because no two cells are exactly the same, different currents will flow through each battery pack due to differing internal resistances, creating difference in state of charge between the two strings. Therefore, for full management with multiple strings, one BMS unit must be used per string, and in some cases, a master controller must be used to manage the whole pack. In the above example, two BMS units, each capable of managing 8 cells in series must be used in conjunction with at least one contactor per string that automatically disconnects the string in the event of a failure, over-charge, over-discharge, or other fault. This is essential to prevent the strings from runaway in the event of imbalance between cells or a cell failure. ***Never leave two lithium ion strings permanently paralleled or leave multiple strings paralleled without monitoring systems and a means of automatic disconnection. As always with any safety critical circuit, always use multiple redundant and independent shutoff systems.***

Difficulties with parallel strings

While it may seem that paralleling multiple strings would increase the overall reliability of a battery pack design, in reality, the opposite is usually true. Unlike lead-acid cells which are commonly assembled in parallel strings, lithium cells are very intolerant of over charge and over discharge. Since lithium cells must be managed on a cell level, parallel lithium strings dramatically increase the complexity and cost of the battery management and introduce many additional points of failure and failure modes not found with a single string. A parallel string topology almost always leads to a lower overall usable capacity and lower maximum power output. A single weak or bad cell can exponentially lower the capacity of the entire battery pack. A properly engineered system can improve the overall reliability, but only when additional equipment and significant engineering time is invested. Whenever possible, a single string set-up should be considered.

Major problems with parallel strings

Eddy currents) When two or more strings are paralleled together, currents will flow between the strings. These currents form due to differences in the total pack voltage between strings. The amount of current that flows is determined by the difference in total string voltages, resistance of each string, and the characteristics of the cells. With these currents, it is possible for one string to force charge a second string, which can lead to over-charging or over-discharging individual cells. A low capacity cell or a faulty cell can cause the force charging of an entire string which may result in over-charge and/or over-discharge. While it seems counter-intuitive, it is possible (in fact, likely) when the charger shuts off due to a fully charged cell in one string, that string may continue to be charged by another parallel string (the same principal applies to discharge). For example, if string A contains a cell which is fully charged, it is possible that current could flow from a second paralleled string B into string A. This would happen every time the average cell voltage in string B was higher than the average cell voltage in string A, even though string A has a cell which has become fully charged (or fully discharged.) This can be compounded by the characteristics of the cells. Most cells have some “surface charge” which causes the cell voltages to artificially rise and drop depending on the recent history of the cell. For example, if it was charged, the voltage will be temporarily raised. Common sense would suggest that these currents would form only when the packs are first paralleled together and then dissipate over time. However, because different currents flow through each string during charge or discharge and due to the surface charge phenomenon, these currents end up being present any time a pack has been charged or discharged. These currents present a significant challenge for managing paralleled strings. **Because of the possibility of these currents, it is absolutely essential that each string MUST have a contactor, shunt trip breaker, or other automatic and redundant means of isolating the string from any other strings if a critical fault occurs. This is in addition to the standard over-current protection for the string. The designer must consider and ensure safe behavior in the event of a failure of any single component, including diodes, contactors, and BMS units.**

Lower maximum usable capacity) Due to the eddy currents mentioned above, headroom must be left at the top and bottom of each cell's voltage and state of charge windows in order to allow for additional charging / discharging after the BMS turns off charging or discharging. This reduces the maximum usable capacity of the pack. The headroom that must be left depends significantly on the cell types, operating temperature range, and quality of the cells.

Exponential impact of one bad cell) While many engineers initially consider using parallel strings to increase redundancy to protect against a bad cell, directly paralleling strings can actually result in a single bad cell having a more significant impact. In a single string, with no cells in parallel, a "bad" cell has a linear impact on the pack's performance. The pack is as strong as the weakest cell in that example. If two cells are paralleled together and then put in series (see Standard Paralleled Cell Configuration above) and one cell were to go bad, the cell which it is paralleled directly to will help prop up the weak or bad cell, limiting the impact of the bad cell. However, if a cell goes bad in a parallel string configuration, it can actually cause an exponential loss of usable capacity in the overall battery pack because of the eddy currents flowing from string to string. In this case, the pack is weaker than the weakest cell. A single weak or bad cell will lower the voltage of the string it is in and cause other paralleled strings to force charge the string with the bad cell. This not only can lead to a dangerous situation where one string gets over-charged while others become over-discharged, but it also exponentially reduces the usable capacity of the entire pack until the string with the bad cell is removed from the system or the bad cell is replaced. With a single string, a new cell with equal or better capacity and resistance can be used to replace a bad cell. However, when replacing a cell in a parallel string pack, a cell of equal characteristics must be used since a cell with a larger capacity or better resistance will alter the currents flowing through each string and cause additional imbalance.

Inrush currents when strings first paralleled) If two strings have different total string voltages, a large current may flow from string to string when they are first connected. When large battery packs which can supply significant currents are used, even very small differences in string voltages can result in significant currents between packs. These currents may damage the battery packs and/or present a safety hazard. It is best to eliminate the possibility of these currents happening at all, but it is absolutely essential to ensure that each string has proper over-current protection such as fuses or circuit breakers. It is also essential that the fuses and breakers are properly sized and have proper interrupting current ratings for the worst case scenario (this calculation must be performed by an electrical engineer). When large currents occur in this situation, they may produce arcing and damaging transients which can damage the cells and/or any equipment connected to the battery pack, such as the BMS. The amount of inrush current is dictated by the difference in the total voltage of the string being introduced and the bus voltage divided by the total resistance (as more packs are added, the overall resistance gets lower, resulting in higher inrush currents).

Less significant issues

Lower maximum power) No two cells are exactly the same and as a result, no two strings will behave exactly the same. Differences in balance within the string, differences in cell resistance, and differences in temperature between strings all result in different amounts of current flowing through each string. This means that strings will never be charged / discharged exactly the same rate. Because of this, two identical parallel strings will never be able to achieve the same power output as if the cells were directly paralleled together and then put in series.

Cascading shutdown) Using multiple strings introduces the possibility of a cascading shutdown. If a single string were to become fully discharged and was suddenly removed from the system, additional load (or charge) would be placed on the remaining strings in the pack. The sudden change in current can draw more power from (or provide more charge to) the remaining strings, which may result in them not being able to handle the load / charge. If that happens, a second string may immediately disconnect, with the remaining load causing the next to shutdown and so forth until all strings disconnect and the load is dropped.

Difficulty calculating amperage limits & state of charge) While calculating limits for each individual string can be done fairly easily, calculating current limits and a total battery pack state of charge for paralleled strings is much more difficult. This is because at any given time, different currents flow through each string due to differences in state of charge, temperature, etc. With the differing currents, and because a single bad cell in one string can cause an exponential loss of capacity in the pack as a whole, predicting when a pack will reach minimum state of charge becomes extremely difficult. This makes paralleled strings significantly less attractive for vehicle applications where state of charge calculations are important.

Individual control of charge and discharge currents) If for whatever reason a string has to be unparalleled from the rest of the strings due to low or high state of charge, the engineer needs to design a means for that pack to be re-introduced safely back into the pack. This can be done manually or automatically by an external controller.

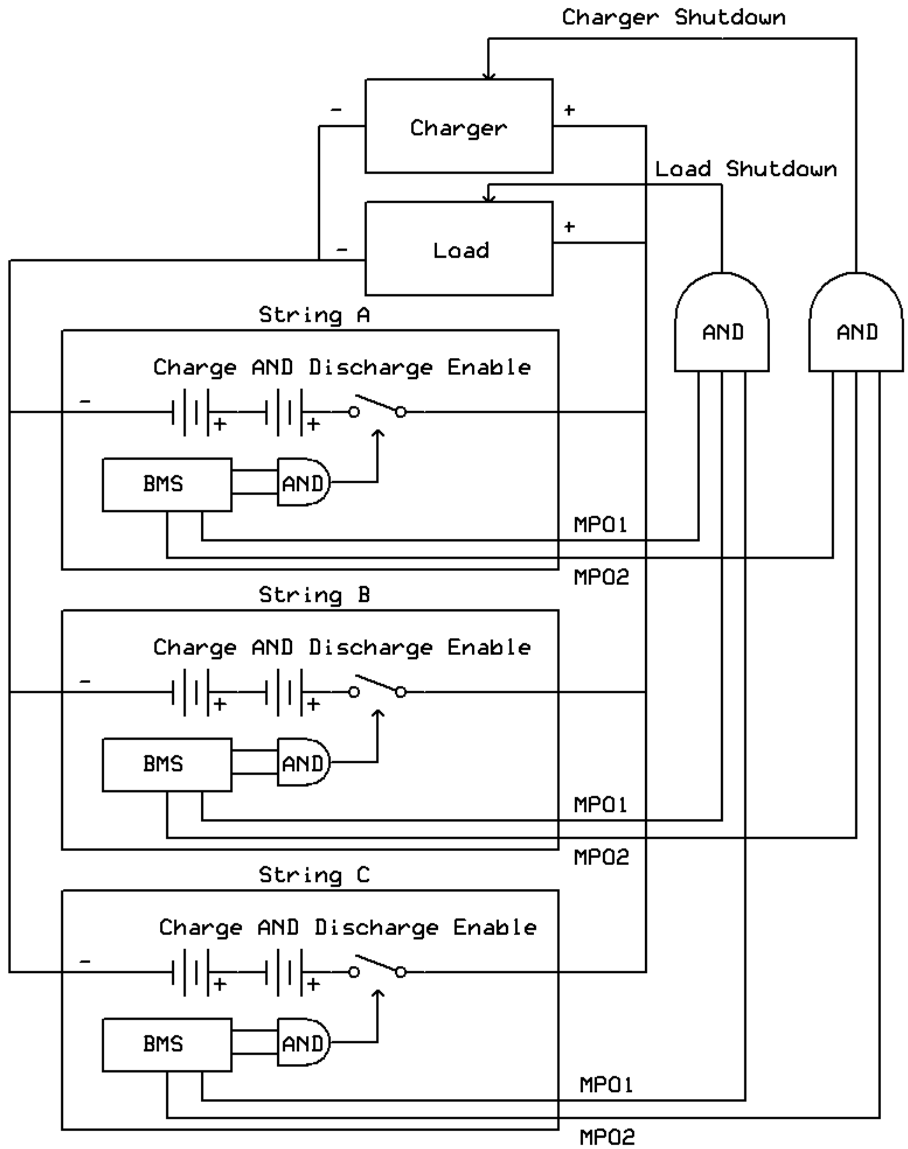
Possibility of interrupted charge power) Some inverters, motor controllers with regenerative breaking, or chargers may fail catastrophically if the DC connection to a battery is interrupted while the charger is active. In some cases, this happens because the charger takes too long to adjust to the change in current. This may result in a high voltage transient that damages the charging equipment. Well designed charging equipment may be designed to handle this condition (always consult with the equipment manufacturer). While this can occur any time the DC connection is interrupted from a charge source, in parallel strings, this can occur as a result of a cascading shutdown where all battery strings are suddenly disconnected.

Parallel String Topologies

The following topologies may be useful for mitigating some of the issues related to parallel strings. While these application notes provide methods for using Orion BMS or Orion Jr. BMS units to protect cells in parallel configurations, it is solely the responsibility of the electrical engineer designing the system to determine the suitability of each of these designs and provide safety systems to prevent dangerous situations. **The designer must consider and ensure safe behavior in the event of a failure of any single component including, but not limited to, diodes, contactors, switches, and the BMS unit.**

Important Note: Due to the risks of parallel strings, additional external safety systems must be used in conjuction with the BMS when the Orion BMS or Orion Jr. BMS are used with parallel strings. Electrical engineering work is required to use the Orion BMS or Orion Jr. BMS with parallel strings, and this work must be performed by an electrical engineer who is trained in working with and understands the risks of paralleled lithium ion batteries. Do not attempt to use parallel strings without proper training.

Standard paralleled strings with just contactors



This approach uses one BMS per string and one contactor per string. The contactor for each string is controlled directly by the BMS on the string. The charge enable and discharge enable are AND'ed together such that the contactor is closed only when the BMS enables charge enable *and* discharge enable. If the BMS stops permitting either charge or discharge, the contactor is opened and the string drops out from parallel.

The goal of this design is to never have a string drop out. To achieve this, a narrower state-of-charge window is used which provides headroom for eddy currents to continue after charging has stopped. As a part of that, reduced upper and lower voltage limits are selected, and the BMS is setup to use two multi-purpose outputs. This feature is currently available in a custom firmware from Ewert Energy. One multi-purpose output is used to signal if discharging must stop due to a low cell voltage, and the other output is used to stop charging due to a high cell voltage (in the restricted state of charge window). By doing this, if any one cell in any string exceeds the reduced upper voltage limit or drops below the lower voltage limit, charging and discharging for the entire battery pack are stopped respectively. Eddy currents will continue to flow between packs after the charge or discharge has stopped to the larger pack. If the eddy currents cause a cell voltage in any string to exceed the absolute maximum voltage or drop below the minimum voltage, the BMS will then turn off the charge enable or discharge enable respectively, opening the contactor for the string in question to prevent damage to that string. Because charge enable and discharge enable on the BMS take into account critical errors, over-temperature, and under-temperature, the BMS will cause the string contactor to open in the event of a critical fault, protecting the string.

In addition to the above mentioned controls, a second system contactor or shunt trip breaker can be used as a secondary shutoff for each string. The BMS is able to trip this secondary contactor or shunt trip breaker off if any cell exceeds the minimum or maximum cell voltage or temperature for more than 10 seconds. This is strongly recommended as a secondary level of defense.

This approach provides basic protection to the cells and strings. However, it results in lower usable capacity and is not very robust. One single bad cell in any string can cause an exponential loss of capacity. Inrush currents are possible when the packs are first paralleled together, and for this reason it may be desirable to use a breaker with a shunt trip such that manual intervention is required in the event that any string were to drop out.

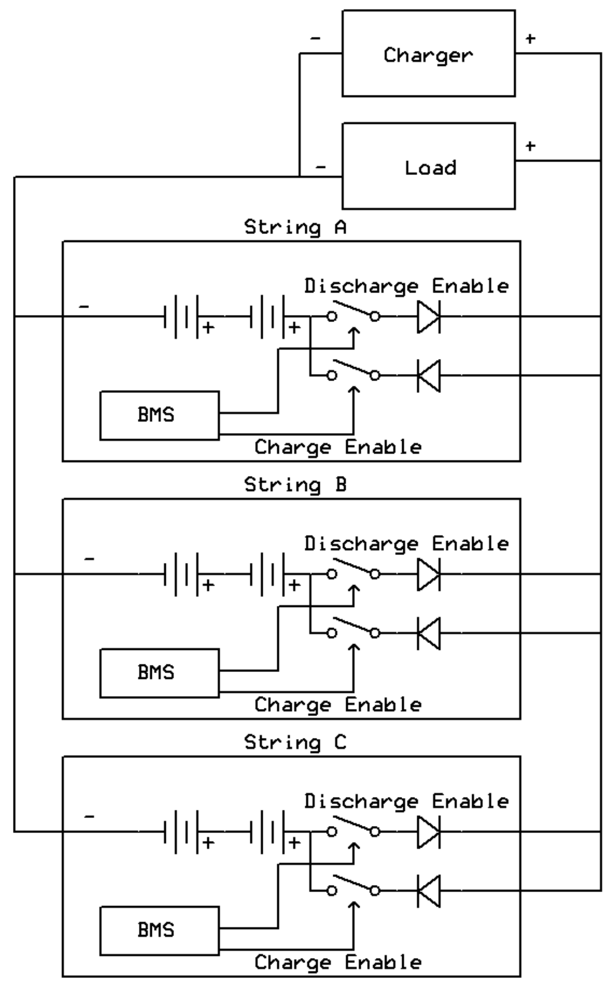
Problems this approach addresses:

- ✓ Protects cells
- ✓ Works with most equipment

Problems this approach does not address:

- × Eddy currents (only somewhat controlled)
- × Lower usable capacity
- × Inrush currents when strings first paralleled
- × Lower maximum power
- × Possibility of cascading shutdown
- × Exponential impact of one bad cell
- × Individual control of charge and discharge currents
- × Possible damage from interrupted charge power (from cascading shutdown)

Paralleled strings with two diodes and two contactors



This approach is very similar to the above approach, but uses two diodes per string to separate out charge and discharge currents for each string. In this configuration, each BMS controls two contactors for the pack directly. Each BMS will operate independently and open the contactor when charge or discharge is no longer permitted for the string.

This approach allows the full use of each string. While eddy currents will still flow from string to string, each string's BMS can individually turn off all charge or discharge for that string. This reduces the need for the headroom for the eddy currents since each BMS can now stop the eddy currents by turning off charge or discharge separately if necessary. Not all equipment will work correctly with this topology, however. For example, most listed battery chargers must measure a voltage on the DC output before they can begin charging. If the BMS on all strings are prohibiting discharge, the charger may not be able to see a DC voltage and may never begin to charge. Some chargers also may become damaged or produce high voltage transients if charge current is suddenly blocked on the DC side of the charger. Care must also be taken to ensure that strings at different voltages are not paralleled together to prevent damaging inrush currents. This is more likely to occur in a configuration where strings are routinely dropped. As with any design, the engineer must design the system to mitigate and detect any single failure, including the failure of a diode or a contactor to weld. The use of a system contactor or shunt trip breaker in each battery pack is strongly recommended as an additional backup.

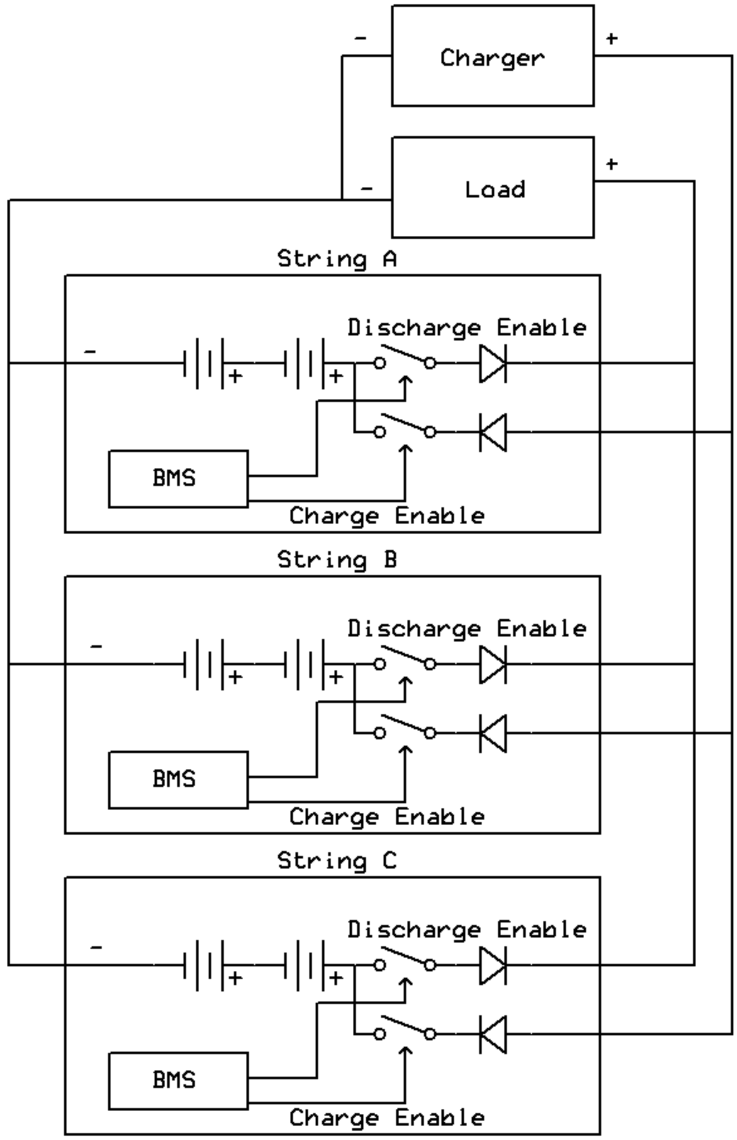
Problems this approach addresses:

- ✓ Protects cells
- ✓ Lower usable capacity
- ✓ Exponential impact of one bad cell (somewhat resolved)
- ✓ Individual control of charge and discharge currents

Problems this approach does not address:

- × Eddy currents (only somewhat controlled)
- × Inrush currents when strings first paralleled
- × Lower maximum power
- × Possibility of cascading shutdown
- × May not work with all equipment
- × Possible damage from interrupted charge power (from cascading shutdown)

Paralleled strings with two separate DC busses



This approach is almost identical to the above approach, with the exception that it uses two separate DC buses – one for charge and one for discharge. In this configuration, the charge and discharge contractors are directly controlled by the BMS in each string.

Since current can only flow in one direction on each bus, eddy currents between strings are completely prevented from occurring in the first place. As this eliminates eddy currents, it also eliminates inrush currents due to differing states of charge when a string is introduced, although the newly introduced pack may still absorb a disproportionate amount of charge or discharge current if introduced at a significantly different state of charge. As with the previous configuration, care must be taken to ensure that any charging equipment can handle a sudden interruption on the DC side of the charger with this approach. As with any design, the engineer must design the system to mitigate and detect any single failure, including the failure of a diode or a contactor to weld. The use of a system contactor or shunt trip breaker in each battery pack is strongly recommended as an additional backup.

Problems this approach addresses:

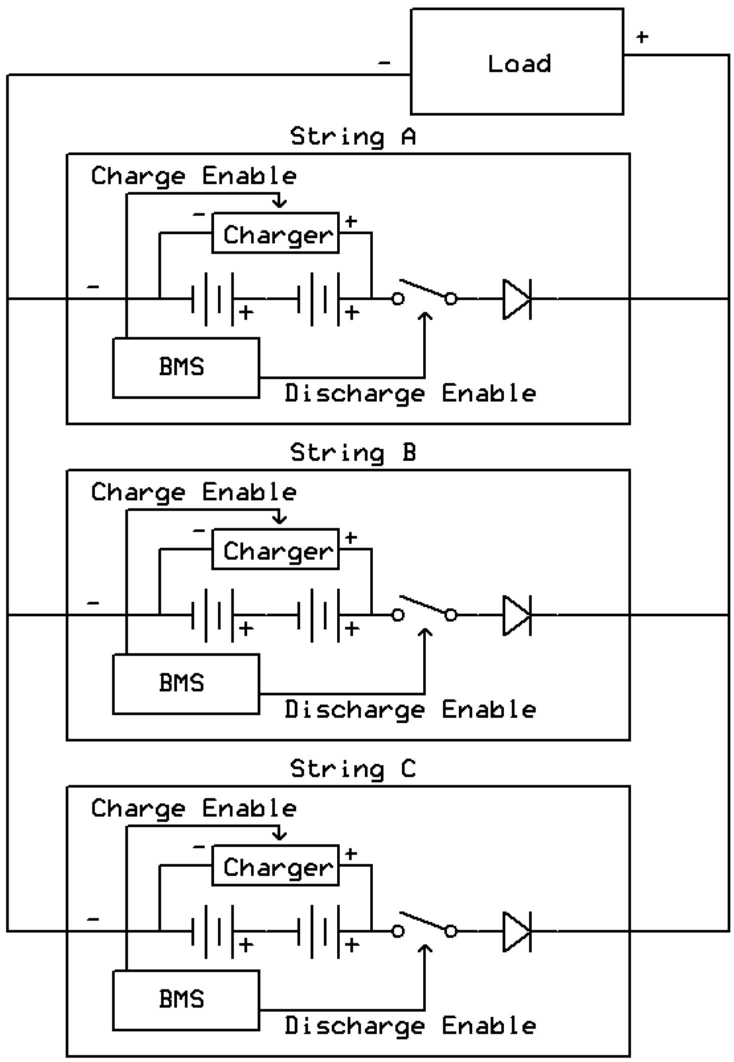
- ✓ Protects cells
- ✓ Eddy currents (completely eliminated)
- ✓ Full usable capacity
- ✓ Inrush currents when strings first paralleled
- ✓ Individual control of charge and discharge currents
- ✓ Exponential impact of one bad cell

Problems this approach does not address:

- × Lower maximum power
- × Possibility of cascading shutdown
- × May not work with all equipment
- × Possible damage from interrupted charge power (from cascading shutdown)

Parallel strings with 1 charger per string and single discharge DC bus

This approach uses one battery charger per string. The BMS in each string directly controls the charger for that string, meaning that the charge can be controlled very precisely. Since the charging is handled and controlled by the charger on each string, each battery pack is only responsible for providing discharge current to the common DC bus.



This completely eliminates the possibility of eddy currents and of damage to the charge equipment since each charger is controlled individually by each string's BMS. While this approach will work with most equipment and presents many benefits, it does not work in situations where a single charge source must be used, such as a bi-directional inverter or motor controller supporting regenerative braking. As with any design, the engineer must design the system to mitigate and detect any single failure, including the failure of a diode or a contactor to weld. The use of a system contactor or shunt trip breaker in each battery pack is strongly recommended as an additional backup.

Problems this approach addresses:

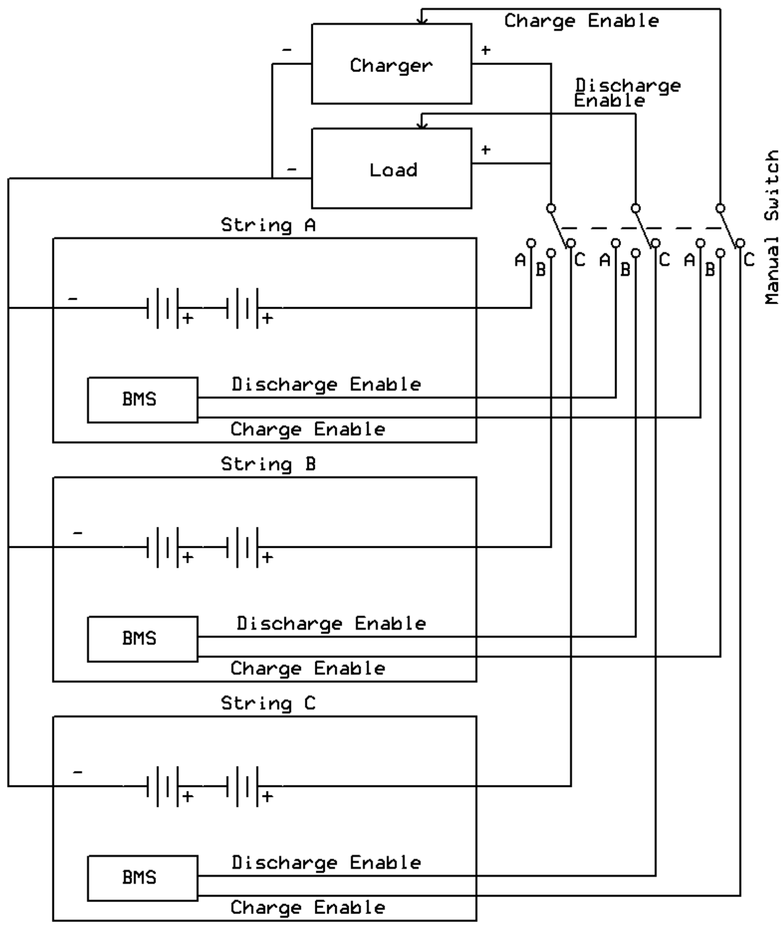
- ✓ Protects cells
- ✓ Eddy currents (completely)
- ✓ Full usable capacity
- ✓ Inrush currents when strings first paralleled
- ✓ Individual control of charge and discharge currents
- ✓ Exponential impact of one bad cell
- ✓ Possible damage from interrupted charge power

Problems this approach does not address:

- ✗ Lower maximum power
- ✗ Possibility of cascading shutdown (only on discharge)
- ✗ May not work with all equipment

String A / String B switch

This is a very simple approach, but it only is appropriate for certain applications. In this approach, either string can be used, but only one string can be used at a time. Because these systems are effectively completely isolated from each other, this approach gives the best redundancy and it completely solves almost all of the potential problems with multiple strings. The down side is that manual intervention or an automatic transfer switch may be required to switch between battery packs.



Switches must be designed to handle making and breaking appropriate currents. Additionally, precautions must be taken to ensure proper signaling is not interrupted between the BMS and the source or loads (such as could happen if a switch were to become faulty). The use of a system contactor in each battery pack or a shunt trip breaker in each battery pack is strongly recommended as an additional backup.

Problems this approach addresses:

- ✓ Protects cells
- ✓ Eddy currents (completely)
- ✓ Full usable capacity
- ✓ Inrush currents when strings first paralleled
- ✓ Individual control of charge and discharge currents
- ✓ Exponential impact of one bad cell
- ✓ Possible damage from interrupted charge power (from cascading shutdown)
- ✓ Possibility of cascading shutdown
- ✓ May not work with all equipment

Problems this approach does not address:

- ✗ Lower maximum power (maximum power will be one string)

Micro-inverters or DC:DC converters

This approach is often the most expensive approach, but it resolves all issues. In this approach, each string is connected to its own charger and load. The chargers and loads may connect to a common AC bus, but the strings are not connected together in any manner. This approach may be applicable for large grid tied solar setups or off grid setups where inverters which can be paralleled on the AC side are used. In this setup, a DC:DC converter could be alternatively used for each string if current was being taken or supplied to a common DC bus.

This approach addresses all issues with parallel strings including maximum power, but depending on the existing requirements, it may be more expensive than other approaches.