Defense Systems
Information Analysis Center

DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

High-Voltage, Direct-Current Battery Management Systems (BMS)

Report Number:
DSIAC-2018-0897
Completed April 2017

DSIAC is a Department of Defense
Information Analysis Center

MAIN OFFICE
4695 Millennium Drive
Belcamp, MD 21017-1505
443-360-4600

REPORT PREPARED BY:

Powers Garmon, Ph.D.
Office: Georgia Tech Research Institute

Scott Armistead
Office: DSIAC

ABOUT DSIAC

The Defense Systems Information Analysis Center (DSIAC) is a U.S. Department of Defense information analysis center sponsored by the Defense Technical Information Center. DSIAC is operated by SURVICE Engineering Company under contract FA8075-14-D-0001.

DSIAC serves as the national clearinghouse for worldwide scientific and technical information for weapon systems; survivability and vulnerability; reliability, maintainability, quality, supportability, and interoperability; advanced materials; military sensing; autonomous systems; energetics; directed energy; and non-lethal weapons. We collect, analyze, synthesize, and disseminate related technical information and data for each of these focus areas.

A chief service of DSIAC is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. For more information about DSIAC and our TI service, please visit www.DSIAC.org.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) received a technical inquiry requesting information on commercial hardware or software applications that detect, manage, and control abnormal and/or dangerous high-voltage lithium-ion battery conditions. The purpose of the inquiry was to determine battery management solutions for military environments. DSIAC staff and academic subject matter experts with experience working on advanced battery development programs performed open-source research of high-voltage lithium-ion battery manufacturers and management systems. DSIAC identified and documented details on five battery management solutions. An inquiry response report was generated and submitted to the inquirer.

Contents

ABOUT DSIAC ii
ABSTRACT iii
List of Tables iv
1.0 TI Request 1
1.1 INQUIRY 1
1.2 DESCRIPTION 1
2.0 TI Response 2
2.1 RELATED TI RESPONSE 2
2.2 OEM SURVEY 2
2.3 OPEN-SOURCE SEARCH 4
REFERENCES 5
APPENDIX A: Battery Management System (BMS) Manufacturer Information ... 8
A-1: ORION BMS 8
A-1.1: Orion BMS Features 9
A-1.2: Orion BMS Components 17
A-2: JTT ELECTRONICS LTD. 18
A-2.1: JTT S-Series BMS Controllers 18
A-2.2: JTT X-Series BMS Controllers 19
A-2.3: JTT Custom Battery Packs 23
A-3: LITHIUM BALANCE A/S 24
A-4: POWERTECH SYSTEMS 25
A-5: ELITHION, INC. 25

List of Tables

Table A-1: JTT Electronics S4 BMS Controller Specifications [34] 20
Table A-2: JTT Electronics X-BCU Master Controller Specifications [36] 22
Table A-3: JTT Electronics X-MCUP Specifications [37] 23

1.0 TI Request

1.1 INQUIRY

Who makes hardware and software solutions for high-voltage lithium-ion (Li-Ion) battery systems?

1.2 DESCRIPTION

The inquirer requested information on manufacturers of safety hardware and software for high-voltage battery systems. Specifically, the inquirer requested information on 1) commercial hardware and software that detects, manages, and controls abnormal conditions in various scenarios of a battery system under charge, under power-drain conditions, or in storage; 2) hardware and software that are tailored to lithium batteries; and 3) redundant features in commercial safe battery management hardware and software.

The inquirer also stated that safety hardware and software must guard against fires or electrical shock and be applicable to cars, aircraft, and boats.

The Defense Systems Information Analysis Center (DSIAC) staff requested clarification on "high-voltage" and "risks." The inquirer responded that anything above 60 volts direct current (VDC) would be considered high-voltage, and risks include water immersion, wire chaffing, battery leakage, and other failure conditions that require monitoring, management, and control of the battery system.

The inquirer's main requirements were the following:

- A market survey of companies developing battery management systems (BMS) with the ability to detect, manage, and control abnormal conditions as well as various scenarios of operation while in storage, under charge, under power drain, or under duress (damage due to collision and/or combat).
- Identification of the design application and what the BMS responds to for an out-of-tolerance condition.

2.0 TI Response

DSIAC staff contacted several BMS original equipment manufacturers (OEMs) and performed an open-source search for relevant information. The open-source search resulted in information from five relevant BMS manufacturers, which was evaluated and compiled (Appendix A). DSIAC staff also provided the inquirer with a relevant TI response that had been completed previously and with information gathered from contact with a BMS OEM.

2.1 RELATED TI RESPONSE

DSIAC staff initially provided the inquirer with a copy of a previous TI response. The TI response, "High Energy Density Li-Ion Batteries with Near Zero Risk of Thermal Propagation," contains information on numerous commercial developers of high-energy lithium-ion (Li-Ion) battery systems and underwater vehicle systems that use the batteries. It also contains information on various Department of Energy organizations and national programs conducting research in this specific area [1].

2.2 OEM SURVEY

DSIAC staff contacted several battery and BMS OEMs, including A123 Systems; Moog, Inc.; Saft; and Quallion LLC (which operates as a subsidiary of EnerSys). Moog was the only OEM that provided detailed data on their BMS. The following is an excerpt of the detailed information provided by Moog [2]:

> Typically, batteries are a grouping of cells in a series/parallel combination to achieve a required voltage and capacity/discharge capability. These packages have a set of electronics that will do everything from simple telemetry (voltage/temperature/etc.) up to fully active load sharing control (active secondary circuit to load share between cells) and/or temperature control (Cooling Loops with forced air/coolant). The intent of these systems is to maintain the battery in as "normalized" of condition as possible, that can mean that all the cells are maintained at as similar of a voltage and discharge capacity as possible and the temperature of the cells being maintained under a manageable threshold.
>
> Water Immersion. Is it spray down or full immersion?
>
> - Mostly these are handled similar to most of our Navy products in that the battery pack would be placed in a sealed box (w/ sealed connectors) and would utilize a compensator to offset the

external pressure differentials by maintaining positive pressure internally.

Wire Chafing.

- This can be mitigated by good design. By this I mean the cabling will need proper sheathing (probably a heavier gauge wire with ~200VDC anyway) so that will reduce the possibility external to the battery pack. Internally the larger battery sizes have a bus bars or heavier gauge wires to connector backshields.

Battery Leakage.

1. Batteries are going to naturally have capacity fade due to either cycle life or calendar life. It is not that they "leak" mechanically, it's that they eventually "leak" electrically, which is sensed as reduced performance. This could be aided or reduced by the BMS design in how much power it draws from the battery and how much power is leaked from the cell parasitically through the switches in the active BMS (if that is how it is designed).
2. There are different types of batteries, some are liquid, some are more solid. Laptop batteries are solid (similar to your electric drill). These are mainly what I am working with. Some batteries use a liquid electrolyte that is added to the battery when it is triggered or ignited. In some senses, these liquid-based batteries could "leak" but to the best of my knowledge this may be more difficult of a proposition because if that was the case, the package would be designed to eliminate that as a failure mechanism.

The following are the parameters that our BMS acts:

- Over temperature.
- Over voltage.
- Under voltage.
- Low remaining State of Charge (SOC) (limited prognostics).
- Heater trigger for low-temperature condition.

Depending on the sensitivity of the application, we have an SOC algorithm that can be implemented on a standard microprocessor that gives a medium-fidelity expectation of charge and power with limited predictions on life expectancy. The simpler applications will use just voltage monitoring and rely on coulomb counting for SOC estimates.

2.3 OPEN-SOURCE SEARCH

A DSIAC subject matter expert from Georgia Tech Research Institute (GTRI) conducted an open-source search. Information on five companies that manufacture hardware and software applicable to the TI request is documented in Appendix A (Orion BMS, JTT Electronics, Lithium Balance, PowerTech Systems, and Elithion). The hardware provided by these companies is tailored to lithium batteries, and all of the vendors support automobiles. A few of the vendors support aircraft and marine applications as well.

GTRI, which is a DSIAC team member, performs basic research and development of advanced technology energy-storage systems such as Li-Ion battery packs that leverage advanced materials-based technologies like the use of graphene. GTRI has the facilities (e.g., Sensors and Electromagnetic Applications Laboratory and Center for Innovative Fuel Cell and Battery Technologies) and research staff necessary to assist government and industry customers in requirements-based design, development, and testing of high-voltage battery packs and the associated BMS. Designs can be configured to maximize the use of commercial off-the-shelf components, as the requirements permit, to reduce cost and schedule.

REFERENCES

[1] DSIAC. "High Energy Density Li-Ion Batteries with Near Zero Risk of Thermal Propagation." https://www.dsiac.org/resources/notable-ti/high-energy-density-li-ion-batteries-near-zero-risk-thermal-propagation, 30 March 2018.

[2] Personal communication with a representative from Moog. 30 March–3 April 2017.

[3] Orion BMS. *Orion BMS Operation Manual Rev 2.1.* https://www.orionbms.com/manuals/pdf/operational_manual.pdf, accessed April 2017.

[4] Orion BMS. "Standard Features." https://www.orionbms.com/features/basic-features, accessed April 2017.

[5] Orion BMS. "Rugged & EMI Resistant." https://www.orionbms.com/features/rugged-and-emi-resistant/, accessed April 2017.

[6] Orion BMS. "Field Programmable." https://www.orionbms.com/features/field-programmable/, accessed April 2017.

[7] Orion BMS. "Charge and Discharge Current Limit Calculation." https://www.orionbms.com/features/current-limit-calculation/, accessed April 2017.

[8] Orion BMS. "Fully Programmable Dual CANBUS Interfaces." https://www.orionbms.com/features/fully-programmable-canbus/, accessed April 2017.

[9] Orion BMS. "State of Charge Calculation with Dynamic Drift." https://www.orionbms.com/features/state-of-charge-with-drift/, accessed April 2017.

[10] Orion BMS. "OBDII & Freeze Frame Diagnostic Support." https://www.orionbms.com/features/obdii-freeze-frame-diagnostic/, accessed April 2017.

[11] Orion BMs. "Battery Health Monitoring." https://www.orionbms.com/features/battery-health-monitoring/, accessed April 2017.

[12] Orion BMS. "Intelligent Cell Balancing." https://www.orionbms.com/features/intelligent-cell-balancing/, accessed April 2017.

[13] Orion BMS. "Reliability, Speed and Accuracy." https://www.orionbms.com/ features/reliability-speed-and-accuracy/, accessed April 2017.

[14] Orion BMS. "Battery Compatibility." https://www.orionbms.com/features/battery-compatibility/, accessed April 2017.

[15] Orion BMS. "Thermal Management." https://www.orionbms.com/features/thermal-management/, accessed April 2017.

[16] Orion BMS. "Integration with Other Devices." https://www.orionbms.com/features/integration-with-other-devices/, accessed April 2017.

[17] Orion BMS. "Multiple BMS Units in Series." https://www.orionbms.com/features/multiple-bms-units-series/, accessed April 2017.

[18] Orion BMS. "Current Sensor Support." https://www.orionbms.com/features/current-sensor-support/, accessed April 2017.

[19] Orion BMS. "Isolated with Fault Detection." https://www.orionbms.com/features/isolated-with-fault-detection/, accessed April 2017.

[20] Orion BMS. "Automotive Grade Design." https://www.orionbms.com/features/automotive-grade-design/, accessed April 2017.

[21] Orion BMS. "PC Software." https://www.orionbms.com/features/pc-software/, accessed April 2017.

[22] Orion BMS. "Other Features." https://www.orionbms.com/features/other-feature/, accessed April 2017.

[23] Orion BMS. "Orion BMS Purchasing Guide." https://www.orionbms.com/manuals/pdf/orionbms_purchasing_guide.pdf, accessed April 2017.

[24] Orion BMS. "Orion BMS 2." https://www.orionbms.com/products/orion-bms-standard/, accessed April 2017.

[25] Orion BMS. "CANdapter – CANBUS to USB Adapter." https://www.orionbms.com/products/candapter/, accessed April 2017.

[26] Orion BMS. "Pre-Wired Harnesses." https://www.orionbms.com/products/pre-wired-harnesses/, accessed April 2017.

[27] Orion BMS. "Cell Wiring Validator." https://www.orionbms.com/products/cell-tap-validator/, accessed April 2017.

[28] Orion BMS. "Basic Display." https://www.orionbms.com/products/basic-display/, accessed April 2017.

[29] Orion BMS. "Thermistor Expansion Module." https://www.orionbms.com/products/thermistor-expansion-module/, accessed April 2017.

[30] Orion BMS. "Data Logging Display." https://www.orionbms.com/products/data-logging-display/, accessed April 2017.

[31] Orion BMS. "Orion Connect – WiFi Expansion Module." https://www.orionbms.com/products/remote-monitoring/, accessed April 2018.

[32] JTT Electronics. "Battery Management Systems." http://www.jttelectronics.com/products/cat/battery-management-systems, accessed April 2017.

[33] JTT Electronics. “S-Series.” http://www.jttelectronics.com/products/cat/battery-management-systems/s-series, accessed April 2017.

[34] JTT Electronics. “S4 BMS Controller.” http://www.jttelectronics.com/products/bms-controllers/s-series/s4-bms-controller, accessed April 2017.

[35] JTT Electronics. “X-Series.” http://www.jttelectronics.com/products/cat/battery-management-systems/x-series, accessed April 2017.

[36] JTT Electronics. “X-BCU Master Controller.” http://www.jttelectronics.com/ products/ battery-management-systems/x-series/x-bcu-master-controller, accessed April 2017.

[37] JTT Electronics. “X-MCUP Controller.” http://www.jttelectronics.com/products/battery-management-systems/x-series/x-mcup-controller, accessed April 2017.

[38] JTT Electronics. “Battery Packs.” http://www.jttelectronics.com/products/cat/battery-packs, accessed April 2017.

[39] Lithium Balance. “Who We Are.” https://www.lithiumbalance.com/en/about-us/who-we-are, accessed April 2017.

[40] Lithium Balance. “Battery Management Systems.” https://www.lithiumbalance.com/en/component/product/categories/19, accessed April 2017.

[41] Lithium Balance. “LiBAL s-BMS.” https://www.lithiumbalance.com/attachments/ product/3_DataSheet_s-BMS%20Housed%20Battery%20Management.pdf, accessed April 2017.

[42] PowerTech Systems. “PowerModule.” https://www.powertechsystems.eu/wp-content/uploads/2016/05/Fiche-Produit-PowerModule_EN.pdf, accessed April 2017.

[43] PowerTech Systems. “About Us.” https://www.powertechsystems.eu/home/about-us/, accessed April 2017.

[44] PowerTech Systems. “Modular Lithium Battery Pack – PowerModule (Voltage up to 700V).” https://www.powertechsystems.eu/home/products/modular-lithium-battery-pack-powermodule/, accessed April 2017.

[45] Elithion. “About Elithion.” http://elithion.com/about.php, accessed April 2017.

[46] Elithion. “Applications.” http://elithion.com/applications.php, accessed April 2017.

[47] Elithion. “Custom Products.” http://elithion.com/custom_products.php, accessed April 2017.

[48] Elithion. “Lithiumate Lithium-ion BMS.” http://elithion.com/lithiumate.php, accessed April 2017.

APPENDIX A: Battery Management System (BMS) Manufacturer Information

A-1: ORION BMS

Orion BMS offers all components (i.e., packaged hardware/software) required to manage large cell-count battery packs, and its battery packs support electric utility vehicles, unmanned aerial vehicles (UAVs) and aircraft, and marine applications. The *Orion BMS Operation Manual Rev 2.1* states the following [3]:

> The Orion 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, the total pack voltage tap, a Hall Effect current sensor, thermistors, a multipurpose input, and an isolation fault detection sensor. 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 or via analog reference voltages or through 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 that respect the current limits set by the BMS 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 unit monitors the voltage of each individual cell (though 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.

A-1.1: Orion BMS Features

A-1.1.1: Basic Features

Excerpt from "Standard Features" by Orion BMS [4]:

> The Orion BMS implements an extensive list of features designed to protect the battery pack. These features include:
>
> - State of charge calculations.
> - Cell over-voltage and under-voltage protection.
> - Intelligent battery balancing (passive).
> - Battery charger control.
> - Pack temperature monitoring.
> - Monitors health of battery pack.
>
> Cells are protected from over-voltage, under-voltage, over-current, over-temperature, and under-temperature based on the programmed minimum and maximum values in the battery profile.
>
> Intelligent, efficient cell by cell balancing is provided to maximize the usable range of the battery. The BMS also monitors the health of both individual cells and the total pack and will trigger error trouble codes if either the pack or individual cells are in poor health.

A-1.1.2: Rugged and Electromagnetic Interference (EMI) Resistant

Excerpt from "Rugged & EMI Resistant" by Orion BMS [5]:

> The Orion BMS is designed at its core to operate in environments with harsh electrical noise such as in electric vehicles. The centralized design allows the Orion BMS to withstand very significant EMI that distributed style systems cannot.
>
> The BMS has undergone testing for noise immunity and has been used successfully in applications where other BMS systems have failed due to excessive noise.

A-1.1.3: Field Programmable

Excerpt from "Field Programmable" by Orion BMS [6]:

> The Orion BMS is designed at the core to be highly programmable. It has the flexibility to be used in both automotive and stationary applications.

The provided software connects to the Orion BMS via CANBUS and can be used to monitor the battery pack, log data, access and clear error codes, update system settings, and change battery profile information.

Battery profiles settings include but are not limited to:

- Minimum and maximum voltages.
- Maximum current limits.
- Open cell voltages for state of charge drift.
- Temperature vs. voltage compensation tables.
- Weak cell thresholds.
- Thermal management settings.
- Charger control settings.
- Selected current sensor.
- Communication (CANBUS) settings.

A-1.1.4: Charge and Discharge Current Limit Calculation

Excerpt from "Charge and Discharge Current Limit Calculation" by Orion BMS [7]:

> While many BMS units simply provide an on/off switch to allow and prohibit discharge and charge currents, the Orion BMS calculates the actual maximum amperage limits such that it prevents the application from drawing the battery voltage above or below the voltage limits.
>
> Other BMS systems simply respond to over-voltage or under-voltage conditions by cutting the limits after the fact. In contrast, the Orion BMS provides the application an accurate view of how much power is available for charge or discharge by actively calculating the values ahead of time.
>
> Pre-calculated current limits are very important in a vehicle application where the main drive computer needs to quickly make decisions based on the power available from the electric system. Failure to have reliable limits can allow the main control computer to draw too much current from the battery, causing the limits to suddenly dive. To respect the new limit, the main drive computer would be forced to reduce current, leading to a jerky or possibly dangerous driving experience.
>
> The limit calculations consider the health of the battery pack, internal resistance, battery temperature, and enforce the maximum pre-set limits in the programmable battery profile for current draw at various temperatures. Values can be expressed in amps or kilowatts for automotive applications.

A-1.1.5: Fully Programmable Dual Controller Area Network (CAN)BUS Interfaces

Excerpt from "Fully Programmable Dual CANBUS Interface" by Orion BMS [8]:

> The Orion BMS features two CANBUS 2.0B interfaces, allowing up to 10 custom messages to be transmitted at regular intervals.
>
> This provides powerful integration capabilities with other CANBUS enabled devices.
>
> Virtually everything about the messages can be customized:
>
> - Identifier (standard or extended).
> - Frequency (speed of broadcast).
> - Message length.
> - Message contents (byte values).
> - Message order (Endianness).
> - Byte order (LSB, MSB).
> - Broadcast on CAN1 or CAN2.
> - Tx in Is-Ready or Is-Charging.
>
> Additional features include:
>
> - Compatible with OBD2.
> - Ability to specify the OBD2 ECU ID.
> - Multiple baud-rates supported (125 Kbps, 250 Kbps, 500 Kbps, 1 Mbps).
> - CAN1 and CAN2 are isolated from each other and may use different baud rates.
> - Mathematical operations can be performed on CANBUS message contents.
> - Can be configured to communicate with J1939 devices and other CAN standards.

A-1.1.6: SOC Calculation with Dynamic Drift

Excerpt from "State of Charge Calculation with Dynamic Drift" by Orion BMS [9]:

> The Orion BMS calculates the state of charge of the battery primarily by tracking the current going in and out of the battery, a technique commonly referred to as coulomb counting.
>
> While this method is accurate, no system is ever perfect. Because of this, the Orion BMS uses settings from the battery profile to look for discrepancies between the calculated state of charge (based on voltage) and the measured state of charge (based on coulomb counting). When

differences are found, the BMS will cause the calculated state of charge to "drift" towards the correct state of charge.

Some other BMS systems correct the state-of-charge instantly rather than drifting. While that may not seem like a problem, external systems are often monitoring the state of charge of the battery and are basing decisions on that number. An SOC drift allows for the state of charge to be adjusted over time, gives advanced warning to other systems, and avoids oscillations.

A-1.1.7: On-Board Diagnostic (OBD)II and Freeze Frame Diagnostic Support

Excerpt from "OBDII & Freeze Frame Diagnostic Support" by Orion BMS [10]:

> Diagnostic Trouble Codes (DTCs, error codes) help with identifying and repairing problems. Error codes are both used for informational purposes and for insuring that a failure of one system does not compromise the performance or reliability of another system.
>
> In addition to simple error codes, the Orion BMS stores freeze frame data (complete snapshot of all parameters at time of code being set) when the error occurs to assist in locating the cause of the error. For OBD-II applications, OBD-II diagnostic trouble codes can be assigned specific DTC handles. For example, a detected fault with the current sensor could set a code "P1234" or "P0030" depending on how it was programmed. This is especially useful in applications where other OBD-II capable systems can also set error codes.

A-1.1.8: Battery Health Monitoring

Excerpt from "Battery Health Monitoring" by Orion BMS [11]:

> One important feature of a battery management system is to provide the user with the overall health of the battery pack. The Orion BMS monitors the internal resistance of each cell and tracks the capacity of the weakest cell. It uses this information to calculate a cell health percentage value from 0 to 100%. The BMS then compares the calculated cell health information against preprogrammed thresholds and if any cells (or the entire pack) fall short of the threshold, a trouble code is set and freeze frame data is stored for later analysis.

A-1.1.9: Intelligent Cell Balancing

Excerpt from "Intelligent Cell Balancing" by Orion BMS [12]:

The Orion BMS uses an intelligent approach to balancing that seeks to maintain and improve balance from cycle to cycle. Unlike lead-acid batteries, lithium ion batteries tend to stay in balance once initially balanced, as long as an intelligent approach is used to maintain the balance.

The Orion BMS uses passive balancing to remove charge from the most charged cells in order to maintain the balance of the pack. The passive shunt resistors dissipate up to 200mA 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 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 200mA balancing current is still 200 times that of the discharge rate.

A-1.1.10: Reliability, Speed, and Accuracy

Excerpt from "Reliability, Speed, and Accuracy" by Orion BMS [13]:

The Orion BMS's centralized design allows it to be more robust and faster than distributed style battery management systems. The BMS measures cell voltages in approximately 30mS, whereas other distributed style systems can take several seconds to measure all cell voltages. This fast speed increases cell life by allowing much faster response in protecting cells from damaging over-voltage or under-voltage conditions that may not even be caught by other slower BMS systems.

Some distributed systems suffer from a complete system communication failure if one cell's voltage drops too low, even for a very brief time. The Orion BMS's centralized design allows the system to continue operating even if multiple cells in the pack briefly dip too low in voltage or completely fail. The Orion BMS is designed to survive in conditions where as many as 65% of cells are at 0 volts.

The Orion BMS is also designed and tested to operate in electric vehicle applications where a very high level of immunity to electromagnetic noise is required.

Accuracy is also an important consideration. Cell voltages are provided with a resolution of approximately 1.5mV with an overall error of < 0.25% across the temperature range.

A-1.1.11: Battery Compatibility

Excerpt from "Battery Compatibility" by Orion BMS [14]:

With a wide voltage sensing range of 0.5v – 5V per cell for monitoring and balancing, the Orion BMS is compatible with virtually all Lithium Ion batteries on the market.

Other BMS systems available cannot be used with certain lower voltage chemistries such as lithium-titanate or higher voltage chemistries that the Orion BMS supports.

The Orion BMS is flexible enough that it works with large format NiMH batteries which operate at much lower voltages than lithium ion batteries.

The BMS is also designed to be used with very high capacity, high power, and high voltage battery packs.

A-1.1.12: Thermal Management

Excerpt from "Thermal Management" by Orion BMS [15]:

The BMS monitors the battery pack temperature through four (4) thermistors directly connected to the main unit. If additional thermistor monitoring is necessary, the Thermistor Expansion Module can be connected to monitor up to 80 additional thermistors, and as many as 10 thermal modules can be used together to monitor 800 thermistors total.

The thermal interface also includes the ability to control an external fan. The controller can be configured for on/off operation or for a variable fan speed using a PWM output. For reliability reasons, the fan driver is external to the BMS and is optional. The fan controller interface includes a fan monitoring circuit which monitors for a malfunctioning cooling fan and can set error codes if a fault is detected.

The fan can be configured both to cool the battery when hot and to warm the battery when warmer ambient air is available. All thermal settings are programmable.

A-1.1.13: Integration with Other Devices

Excerpt from "Integration with Other Devices" by Orion BMS [16]:

To provide maximum support for interfacing with external devices (such as chargers, motor controllers, power inverters, etc.), the Orion BMS has several different types of outputs.

The digital output signals provide ON/OFF control. The 5V analog voltage outputs allow for current limiting based on an analog voltage and can also be used for interfacing with gauges and meters.

A-1.1.14: Multiple BMS Units in Series

Excerpt from "Multiple BMS Units in Series" by Orion BMS [17]:

> In circumstances where battery packs have more than 180 cells in series or if the battery pack is split into multiple remote locations, two or more Orion BMS units can be used together in series.
>
> This method allows for monitoring battery packs up to 2000v if appropriate safety measures are taken.

A-1.1.15: Current Sensor Support

Excerpt from "Current Sensor Support" by Orion BMS [18]:

> Many current sensor options are available. Current sensors should be chosen based on the maximum amperage for a particular application.

A-1.1.16: Isolated with Fault Detection

Excerpt from "Isolated with Fault Detection" by Orion BMS [19]:

> In designs using high voltage or high power lithium ion batteries, it is often necessary for battery packs to be isolated from the chassis for safety reasons. In these situations, active monitoring is necessary to ensure that no breakdowns of insulation have occurred.
>
> The Orion BMS provides 2.5kV isolation between the chassis and voltage taps, as well as between groups of 36 cells for safety disconnects and fuses. 2kV Isolation is provided between the total pack voltage sensor and the control electronics/chassis.
>
> The Orion BMS features real, active isolation fault detection that can alert the user to very small breakdowns in insulation before they become a larger problem. Unlike with other systems on the market, this feature is standard on the Orion BMS and is integrated into the central unit.

A-1.1.17: Automotive Grade Design

Excerpt from "Automotive Grade Design" by Orion BMS [20]:

> The Orion BMS is designed to operate through the voltage transients and electrical noise commonly produced by inverters, motor controllers, and chargers in electric vehicles. These voltage transients and radiated/ conducted electrical noise often cause other BMS units to fail.
>
> The Orion BMS is rated for the full automotive temperature range of -40C to +80C. The connectors are vibration resistant, fully locking automotive-

grade connectors. The BMS has undergone 1 meter drop tests for mechanical shock, ESD, and EMC testing. The integrated heat-sink eliminates the need for active cooling.

Additionally, the current sensors sold with the BMS are automotive-grade, are dual range for increased accuracy and redundancy, and are stable across the full operating temperature range.

The BMS features a low power sleep mode where data is retained while the vehicle is off, but the system is ready to resume operation quickly.

A-1.1.18: PC Software

Excerpt from "PC Software" by Orion BMS [21]:

The software provided with the Orion BMS can be used to program the BMS, display live data, read and clear trouble codes, and graph and log real-time data.

Here are some additional software features:

- Easy to use and intuitive
- Uses the CANdapter to communicate with the Orion BMS
- Can pull freeze frame snapshots for diagnostics
- Displays individual cell voltages
- Shows all parameters calculated by BMS
- Can upload and download battery profiles (settings) from the BMS
- Works on Windows, Linux, and other operating systems

A-1.1.19: Additional Features

Excerpt from "Other Features" by Orion BMS [22]:

Some additional features of the Orion BMS include:

- Open cell voltage calculation – The cell's voltage is calculated as if the cell had no load applied. This data is mostly used for internal calculations but is provided to the user.
- Redundant parallel cell monitoring – The same cell can be monitored more than once to increase redundancy and double the balancing current (see manual for important details on proper wiring for this.)
- Busbar resistance compensation – The Orion BMS can compensate out extra resistance from longer busbars or cables between batteries. For very high resistance cables, additional

wiring precautions must be taken (see wiring manual for more details.)

- Heartbeat monitoring of other ECUs (electronic control units) – The BMS has the ability to look for CAN activity from other ECUs. If traffic stops, the BMS can set an error code. This can be used for cross checking other ECUs.

A-1.2: Orion BMS Components

Orion BMS components are described in the "Orion BMS Purchasing Guide." The components include the following [23]:

- Orion BMS Unit.
  - For more information, see "Orion BMS 2" by Orion BMS at the following link: https://www.orionbms.com/products/orion-bms-standard/ [24].
- CANdapter.
  - For more information, see "CANdapter – CANBUS to USB Adapter" by Orion BMS at the following link: https://www.orionbms.com/products/candapter/ [25].
- Wiring Harnesses.
  - For more information, see "Pre-Wired Harnesses" by Orion BMS at the following link: https://www.orionbms.com/products/pre-wired-harnesses/ [26].
- Cell Wiring Validator.
  - For more information, see "Cell Wiring Validator" by Orion BMS at the following link: https://www.orionbms.com/products/cell-tap-validator/ [27].
- Basic State of Charge (SOC) Display.
  - For more information, see "Basic Display" by Orion BMS at the following link: https://www.orionbms.com/products/basic-display/ [28].
- Thermistor Expansion Module.
  - For more information, see "Thermistor Expansion Module" by Orion BMS at the following link: https://www.orionbms.com/products/thermistor-expansion-module/ [29].
- Data Logging Display Module.
  - For more information, see "Data Logging Display" by Orion BMS at the following link: https://www.orionbms.com/products/data-logging-display/ [30].
- Remote Monitoring.
  - For more information, see "Orion Connect – WiFi Expansion Module" by Orion BMS at the following link: https://www.orionbms.com/products/remote-monitoring/ [31].

A-2: JTT ELECTRONICS LTD.

JTT Electronics battery management systems monitor Li-Ion battery packs to enhance performance and ensure safe operating conditions. They are used in hybrid vehicles, electric vehicles, backup power systems and other applications, but marine applications may be an issue. JTT Electronics can provide custom solutions that include high-voltage battery packs integrated with a fully configured BMS suited to the application. The S-Series and X-Series BMS products are particularly relevant to the TI request [32].

A-2.1: JTT S-Series BMS Controllers

JTT Electronics offers four different controller options in the S-Series, which vary in voltage and number of cells. The S-Series controller that is relevant to the TI request is the S-4 BMS controller [33].

Excerpt from "S4 BMS Controller" by JTT Electronics LTD [34]:

> The S4 BMS controller is designed for low to medium voltage lithium-ion battery systems and supports 4 separate cell banks. Each cell bank can have 4–12 cells in series, for a total of 16–48 cells [34].
>
> Originally developed for use in electric vehicles, the S4 controller's standalone design is highly configurable for many different applications. Features include built-in relay control, an isolated CAN bus and isolated RS-232 for communications, 6 configurable digital or analog inputs/outputs, redundant hardware safety disconnect, voltage and temperature monitoring for every lithium-ion cell, and a battery output current sensor.

S4 BMS controller features include the following [34]:

- Intelligent Monitoring
  - All cell voltages and temperatures.
  - Battery pack current.
  - Dynamic SOC and State of Health (SOH) algorithms adapt to aging cells.
  - Capacity and direct-current (DC) resistance calculations.
  - Over 80 fault conditions monitored at all times.
  - Configurable alarm levels.
- Efficient Design
  - Dual-layer safety architecture (hardware and software).
  - Automotive-grade components.
  - Extremely low-power dissipation.

  - 300 mA passive cell balancing.
  - IP55 protection rating.
  - Isolated CAN bus channel.
  - Configurable inputs and outputs.

- Comprehensive Data Management.
  - Cell lifetime data recorded in controller memory.
  - Integrated BMS Link software for laptops or PCs allows data monitoring and export, direct battery pack control, and problem diagnosis.

The S4 BMS controller specifications are presented in Table A-1.

A-2.2: JTT X-Series BMS Controllers

Excerpt from "X-Series" by JTT Electronics [35]:

> The X-Series BMS controllers are typically used with medium- to high-voltage battery packs for mobile applications, full electric and hybrid electric vehicles (including city buses), and industrial machines. The X-Series' patent-pending design includes features to increase safety and intelligently manage inter-controller communications.

There are two versions of the X-Series controller (X-BCU and X-MCUP) that are relevant to the TI request.

A-2.2.1: JTT X-Series X-BCU Master Controller

Excerpt from "X-BCU Master Controller" by JTT Electronics [36]:

> In the X-Series BMS, the X-BCU provides total system monitoring and control, while the X-MCUP controllers manage battery cells directly. The X-BCU master controller supports connectivity for up to 20 X-MCUP controllers.
>
> Originally developed for use in electric buses, the X-Series BMS's patent-pending expandable design is best suited for medium- to high-voltage lithium-ion battery packs and is highly configurable for many different applications. Features include isolated CAN bus communications, support for up to 240 cells, and automatic configuration of X-MCUP modules upon connection to the X-BCU master.

Table A-1: JTT Electronics S4 BMS Controller Specifications [34]

Parameter	Value
Supply Voltage	9–32 V
Number of Cells	4–48
Battery Voltage	up to 220 V
Cell Voltage Monitoring and Hardware Interlock	
Measurement Resolution	1.5 mV
Measurement Gain Error	±0.12 %
Range	0–5 V
Measurement Period	50 ms
Cell Temperature Monitoring	
Cell Temperature Measurement Resolution	0.1 °C
Cell Temperature Measurement Accuracy	1.0 %
Cell Temperature Measurement Range	-100–100 °C
Cell Balancing	
Passive Balancing Current	250–300 mA
Current Sensor	
Automotive Dual-Range Hall Effect Sensor	
Communications	
Isolated CAN Bus	1
CAN Bus (diagnostic)	1
Isolated RS-232	1
Input/Output (I/O)	
High-Power Driver (1 A)	2
Digital I/O (750 mA)	4
Digital I/O (750 mA) **OR** Analog Output (0–5 V)	2

X-BCU features include the following [36]:

- Intelligent Monitoring.
    - Automatic X-MCUP module detection and configuration.
    - Comprehensive system high-voltage monitoring.
    - Dynamic SOC and SOH algorithms that adapt to aging cells.
    - Over 80 fault conditions that are monitored at all times.
    - Regulated power output for X-MCUP controllers.
    - Ground fault detection.
- Efficient Design.
    - Automotive-grade components.
    - Extremely low-power dissipation.
    - Configurable alarm levels.
    - IP55 protection rating.
    - Isolated CAN bus channels.
    - Configurable inputs and outputs.
- Comprehensive Data Management.
    - Cell lifetime data recorded in controller memory.
    - Integrated BMS Link software for a laptop or PC allows users to monitor and export data, control the battery pack directly, and diagnose problems.

The X-BCU master controller specifications are provided in Table A-2.

A-2.2.2: JTT X-Series X-MCUP Controller

Excerpt from "X-MCUP Controller" by JTT Electronics [37]:

> The X-MCUP controllers manage battery cells directly, while the X-BCU provides total system monitoring and control. Each X-MCUP supports a single cell bank of 4–12 cells in series.
>
> Originally developed for use in electric buses, the X-Series BMS's patent-pending expandable design is best suited for medium- to high-voltage lithium-ion battery packs and is highly configurable for many different applications. Features include isolated CAN bus communications, support for up to 240 cells, and automatic configuration of X-MCUP modules upon connection to the X-BCU master.

Table A-2: JTT Electronics X-BCU Master Controller Specifications [36]

Parameter	Value
Supply Voltage	9–32 V
Number of X-MCUP modules	1–20
Battery Voltage	up to 1000 V
X-MCUP Power Supply	
Output Voltage	24 V
Output Current	3.7 A
Current Protection	3.8 A
Battery Voltage Monitoring	
Range (full)	0-1000 V
Accuracy	0.1 %
Current Sensor	
Automotive Dual-Range Hall Effect Sensor	
Communications	
Isolated CAN Bus (diagnostics and MCUP communication)	1
Isolated CAN Bus (protocol configurable)	2
I/O	
High-Power Driver (1 A)	5
Digital Input	5
Digital Output (750 mA)	1

X-MCUP features include the following [37]:

- Intelligent Monitoring.
    - Up to 12 cell voltages and temperatures.
    - Capacity and DC resistance calculations.
    - Dynamic SOC and SOH algorithms adapt to aging cells.
    - Transmits all information to the X-BCU master controller for additional monitoring and control.
- Efficient Design.
    - Dual-layer safety architecture (hardware and software).
    - Automotive grade components.
    - Extremely low-power dissipation.
    - 300 mA passive cell balancing.

  - IP55 protection rating.
  - Isolated CAN bus channel for communication with the X-BCU.
  - Configurable inputs and outputs on every unit.

- Comprehensive Data Management.
  - Cell lifetime data recorded in controller memory.
  - Integrated BMS Link software for laptops or PCs allows data monitoring and export, direct battery pack control, and problem diagnosis.

The X-MCUP controller specifications are provided in Table A-3.

Table A-3: JTT Electronics X-MCUP Specifications [37]

Parameter	Value
Supply Voltage	9–32 V
Number of Cells	4–12
Battery Voltage	up to 55 V
Cell Voltage Monitoring and Hardware Interlock	
Measurement Resolution	1.5 mV
Measurement Gain Error	±0.12 %
Range	0–5 V
Measurement Period	50 ms
Cell Temperature Monitoring	
Cell Temperature Measurement Resolution	0.1 °C
Cell Temperature Measurement Accuracy	1.0 %
Cell Temperature Measurement Range	-100–100 °C
Cell Balancing	
Passive Balancing Current	250–300 mA
Communications	
Isolated CAN Bus (Diagnostics and BCU Communication)	1
I/O	
Digital I/O (750 mA)	2
Digital Output (750 mA)	2

A-2.3: JTT Custom Battery Packs

JTT Electronics can also design battery packs for a customer's specific application. JTT battery packs come fully configured with lithium-ion cells chosen specifically for the application after

extensive testing. Cell testing ensures complete battery pack optimization. The battery pack will be integrated with a fully configured BMS suited to the application [38].

A-3: LITHIUM BALANCE A/S

Lithium Balance is a Danish company that manufactures BMS for lithium battery packs [39]. The s-BMS can be used in automotive applications, but battery-pack marine applications may be an issue.

Excerpt from "Battery Management Systems" by Lithium Balance [40]:

> The s-BMS is an exceptionally flexible and cost efficient Battery Management System for automotive, industrial, and storage stationary battery packs ranging from 12VDC up to 1000VDC. The renown s-BMS is one of the most robust systems available on the market and has been tested for extremely harsh environments, e.g., -90C to +120C, vibrations HALT test on three axes ...etc. The system can be fully configured at bit level using a LiBAL PC management tool via CAN bus.
>
> It comes in different mechanical designs either as integration PCB boards or packed in a housed solution for applications where IP6x rated protection is required. There are two versions of the s-BMS, a full blown version featuring up to 256 battery cells and a limited one up to 16 cells. Finally the s-BMS is an intelligent system that manages rechargeable Li-batteries of any chemistry and from any supplier, allowing you maximum sourcing freedom.

Excerpt from "LiBAL s-BMS" by Lithium Balance [41]:

> The master Control Unit monitors up to 16 cells in series and can be used stand alone as a 12-48VDC BMS. But it can also daisy chain up to 15 Monitoring Units, each of which can monitor another 16 cells. Both units are rated IP61 with casings designed to dissipate heat and comes with a family of dedicated cables.
>
> The PC Diagnostic Software provides displays for monitoring battery and BMS performance. It also allows you to configure all battery parameters such as limit voltages and temperatures, allowable charge and discharge rates, or improve SoC estimation with your own battery model.
>
> CAN frames can be constructed at "Bit level" to broadcast the parameters measured and calculated. A post processing module allows you to scale and manipulate values and broadcast them on the CAN bus with no custom development needed. This allows the

s-BMS to work as a drop-in replacement for many existing systems.

A-4: POWERTECH SYSTEMS

PowerTech advertises a "plug-and-play" system called PowerModule. It comprises a battery pack and BMS, and it is a self-contained system [42].

Excerpt from "About Us" by PowerTech Systems [43]:

> PowerTech Systems is a French company focused on the Lithium-Ion storage market and associated technologies. They specialize in the design and engineering of high-performance Lithium batteries (> 1KW) covering a large application spectrum (vehicle traction, stationary storage, Off-Grid, etc.).

Excerpt from "Modular Lithium Battery Pack – PowerModule (Voltage up to 700V)" by PowerTech [44]:

> PowerModule batteries are advanced energy solutions for traction applications requiring high capacity and/or high voltage (up to 700 volts). The modules can be connected in series or parallel to increase capacity or voltage. Up to 255 modules can be assembled in series or parallel. Systems have two levels of security to ensure optimal level of operation: each module embeds a slave BMS and an external BMS is dedicated to module management.
>
> Each 12V Lithium-ion module has a built-in BMS that monitors operating conditions (temperature, over voltage, under voltage, etc.). An external BMS ensures optimal operation by a real-time monitoring of each module (up to 255).

A-5: ELITHION, INC.

Excerpt from "About Elithion" by Elithion [45]:

> Elithion is a privately held Corporation in Boulder, Colorado, dedicated to the development and marketing of electronic solutions for the Lithium Ion battery industry.
>
> Elithion designs and manufactures Battery Management Systems (BMS), large Li-ion packs and battery modules for stationary battery installations.
>
> The Elithion team has comprehensive experience in electronics design as well as extensive expertise in validated and proven battery systems

engineering. Their capabilities include working with large cell suppliers and integrating custom solutions.

Elithion products can be used in various applications, such as lawn mowers, electric vehicles, airplanes, robots, sea-port tugs, solar systems, and cell-phone towers. Elithion also supports marine applications like power plants [46].

Elithion offers several battery management products, but their Lithiumate Lithium-ion BMS is relevant to the inquiry. Elithion also offers custom BMS and large battery packs [47].

Excerpt from "Lithiumate Lithium-ion BMS" by Elithion [48]:

> This Li-ion Battery Management System monitors, evaluates, balances, and protects a Li-Ion battery pack. Features include:
>
> - Off the shelf, plug-and-play Lithium-ion BMS.
> - For professional applications: commercial grade, metal case (not sealed).
> - Distributed (a cell board is mounted on each cell: measures voltage and temperature, balances the cell).
> - Minimum number of wires in HV pack, single wire to adjacent cell boards.
> - For large packs: up to 255 cells (~ 900 V), in up to 16 banks, and up to 16 strings in parallel.
> - Supports all cell form factors: prismatic, small and large cylindrical, pouch.
> - Supports mid-voltage Lithium-ion chemistries:
>   - Lithium iron phosphate (LFP): LiFePO4, LiFeYPO4.
>   - LiCoO2 (LCO) - Lithium cobalt oxide.
>   - LiMn2O4 (LMO) - Lithium manganese oxide.
>   - LiNiMnCoO2 (NMC) - Lithium nickel manganese cobalt oxide.
>   - LiNiCoAlO2 (NCA) - Lithium nickel cobalt aluminum oxide.
> - Protects cells from over current, under/over voltage, under/over temperature.
> - Dissipative (passive) balancing (top balance).
> - Sophisticated, digital technology: reports each cell's voltage and temperature.
> - CAN and RS232 communications.
> - Fully configurable, field programmable.
> - Cable mount Hall Effect current sensor.
> - Contactor drivers with pre-charge.
> - Optical isolation between pack and low-voltage circuit.

- Pack isolation loss detection (optional).
- Compatible with various chargers.
- Compatible with various motor drivers.
- Graphics User Interface.