Electrical Inspection

Battery Protection System Test Procedure

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Revision History

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Approval

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Introduction

This document is a reference for teams to outline the basic inspection process and requirements for the vehicle Battery Protection System (BPS) as described in section 5.4 of the ASC2016 regulations. The objective of the BPS inspection is to field test the functional transition and isolation of the storage battery system under each fault condition. The net result is to demonstrate each team's BPS ability to electrically isolate the battery back from vehicle's electrical load. Battery chemistries not required to show electrical isolation must demonstrate means of active monitoring. This document will focus on the BPS systems dealing with Lithium battery technology due to the stricter requirements. The complete regulation details for the vehicle electrical system can be found on the ASC website under regulations.

The definitions for common terminology used in this document:

Word	Definition
Cell	The smallest available source of energy in your battery pack that you purchase from a manufacturer. A single electrochemical cell.
Module	The smallest easily removable group in your battery, typically paralleled.
String	The series group of cells needed in your battery pack that provide the required voltage.
Protection Limit	The measured level that your team decides is adequate to protect from an event.
Active	Active means constantly monitored measurements where action can be taken immediately without operator intervention.

Table 1 – Common terminology definitions

Due to the limits in time and resources during the inspection process, it is important teams consider accessibility that meets the objectives of this test process. While the inspection team will try it's best to accommodate the variety of system designs teams will have, it is to the advantage of the team to make their systems easy to access, inspect, test, and calibrate. The test procedure is not meant to guarantee the operation or reliability of the protection system under all possible conditions. Teams should thoroughly document, calibrate, test, and maintain their systems before and after the inspection.

Teams using this document are advised to report any inaccuracies or suggested changes within the document to ASC headquarters for proper resolution (ascinfo@americansolarchallenge.org). Examples and drawing in this document should not be interpreted as the only correct solution. Modifications in the process can be implemented on a case-by-case basis by the inspection team.

Test Objectives

Fault Conditions by Battery Chemistry

Depending on the chemistry used, it is expected the protection system to electrically isolate the battery pack for the following conditions based on the protection limits defined by the battery manufacturer: **Over-Voltage(OV)**, **Under-Voltage(UV)**, **Over-Current(OC)**, and **Over-Temperature(OT)**. These limits can further be divided into **Over-Current Charging(OCC)**, **Over-Current Discharging(OCD)**, **Over-Temperature Charging(OTC)**, and **Over-Temperature Discharging(OTD)** based on the chemistry required operational set points. The system must actively monitor these conditions and react immediately and independently of the driver in reaction to the fault condition(s). All protection faults will latch such that a manual clearing process is required while the vehicle is not in motion and only after all faults have been verified clear by the protection system. The fault clearing process is strongly suggested to include someone other than the diver that can visually inspect the battery pack. Battery chemistries that do not require active isolation will show passive monitoring of measurements monitored by the driver. All meters will need labeling that designate the value at which the driver should take action.

Battery Chemistry –

Li-Ion – Battery packs require active monitoring protection for OV, OC, UV and OT with electrical isolation of all sources and sinks. Protection down to module or cell will be required depending on the battery manufacture.

NiMH/NiCd – Must be protected from OV and OT at pack level. Active protection with isolation is not required but recommended if passive monitoring is unavailable.

Pb-Acid – Must be protected from OV at pack level. Active protection with isolation is not required but recommended if passive monitoring is unavailable.

Hybrid Packs – Must be appropriately protected for each chemistry type with appropriate protection limits specified by the manufacture.

Supplemental Batteries – Require fusing as documented in the regulations. All supplemental batteries must have at a minimum Passive Protection for under voltage where charging occurs remote to the solar vehicle unless they are primary cells. Charging for the supplemental battery must be done outside the car with a charger that has OV protection. It is strongly recommended for supplemental battery powering the isolation relays to have active monitoring. Active Protection is required if charging is within the solar vehicle.

Special Consideration

A battery management system(BMS) which optimizes the battery pack's performance or other car power functions, if implemented, must operate independently of the BPS. Common BMS functions primarily for lithium battery systems includes telemetry, metering, thermal management, capacity monitoring, and cell balancing. A proper BMS should control the state of the battery pack source and sink requirements so as to never reach the BPS limits as in **Figure 1**. If the BPS and BMS software operates on common hardware then no BMS functions with other systems, inputs, or driver activities should preempt or interfere with the BPS automatic and immediate function to protect the batteries from each fault condition. Additionally, each team should be aware of the impact the protection system isolation has on the other systems in their vehicle. Limits on other electrical system source(array and regen) and sink(motor) values are important system operational characteristics but do not substitute for a complete BPS.

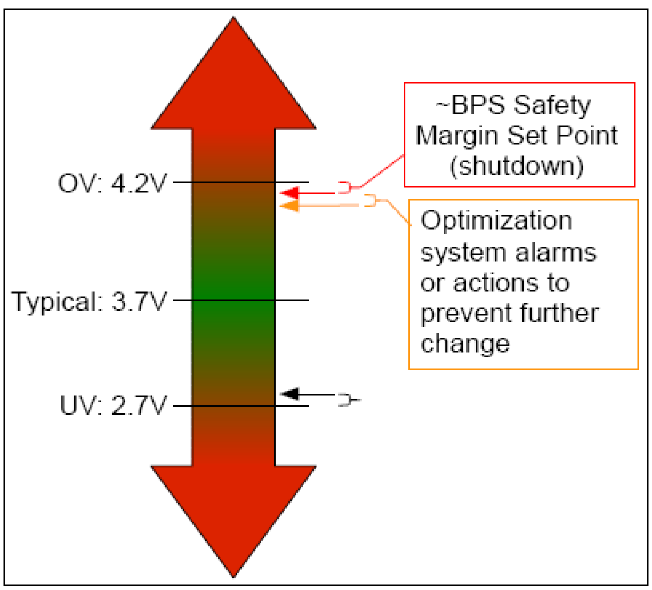

Figure 1 – Example Cell Voltage Operational Range

Vehicle Electrical Systems

The Complete System

Each vehicle will have a basic electrical system composed of a solar array, storage battery, and motor. As seen in the system diagram for **Figure 2** the battery and protection system are electrically tied to both power sourcing elements like the array or motor in regen, and sinking element of the motor. Protection circuitry will integrate with the vehicles battery pack to at a minimum provide active monitoring of the batteries at all times. Lithium packs will also require the protection circuitry to have the ability to actively isolate the battery from all other sub-systems.

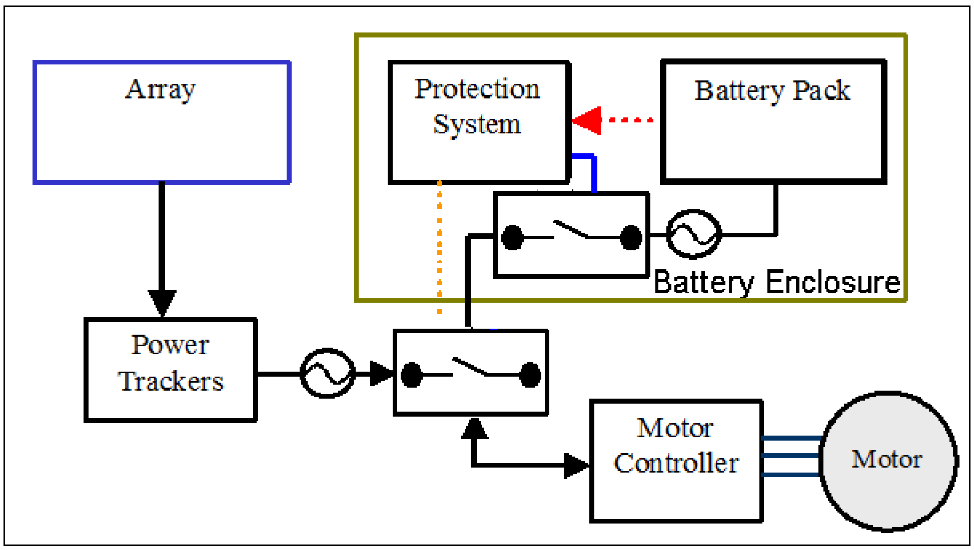

Figure 2 – Common Systems

Battery Protection System

Like the vehicle's electrical systems, the Battery Protection System(BPS) integrates with multiple subcomponents. Its placement within the battery pack should be considered with the battery enclosure design. This is due to the requirement that the battery pack will be removed each day for impound. Connection points and wiring chaffing are two points to consider in how the components are link together. **Figure 3** shows a basic system diagram of the Battery protection system and its connectivity.

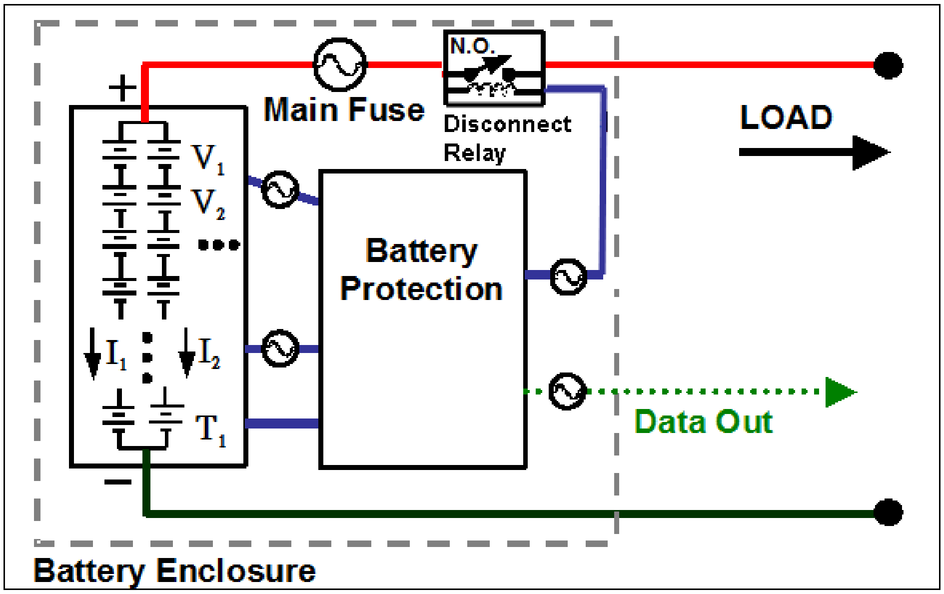

Figure 3 – Common terminology definitions

The definitions for the four fault conditions the battery protection system evaluates are listed in **Table 2** with examples of possible reasons.

Word	Definition	Reason
Over-Voltage(OV)	When module or possible cell voltage reaches maximum manufacture rated cell voltage: $\mathbf{V_{1,2,...} = V_{max}}$	Over charging from array, excess regen, pack imbalance
Under-Voltage(UV)	When module or possible cell voltage reaches minimum manufacture rated cell voltage: $\mathbf{V_{1,2,...} = V_{min}}$	Excessive draw on battery, missing low battery set point on motor controller, low charge, pack imbalance
Over-Current(OC)	When battery string or possible cell current reaches maximum manufacture rated current for charging or discharge condition: $\mathbf{I_{1,2,...} = I_{max}}$	Improperly configured pack, current limiting set point on motor regen
Over-Temperature(OT)	When the pack, module, or possible cell temperature reaches the manufactures maximum rating during charge or discharge: $\mathbf{T_{1,2,...} = T_{max}}$	High charge or discharge rate, over charging, loss of airflow, temperature in environment too high

Table 2 – Fault Condition Parameters

Test Process, Electrical (BPS) Scrutineering

As stated at the beginning of the document there will be limits on time and resources during the inspection process, so it is in every team's best interest to be prepared to meet the objectives of this test process. The BPS test scenarios for each fault condition will include the electrical isolation of sensor inputs that measure voltage, current, and temperature in the pack. Then by supplying a control signal of appropriate magnitude cause the protection system to trip for each fault condition.

The preference of the inspection team is to have a set of easily accessible test points on the outside of the battery enclosure or protection system. The battery system must only show the resulting electrical isolation so it would be possible for the test to be performed with the battery pack in or next to the vehicle. An injected signal level along with a Digital Multi-Meter(DMM) would be used to validate each trip point for the protection conditions. One would envision a 3-way switch in line that would connect to a set of test points accessible by DMM. The first switch position for the pack is the actual operational mode for the sense lead. The second position supplies the actual packs value to the test point so we would see the value going to the protection system and the third would isolate the sense lead back into the protection system. A small reference signal from an isolated source would be used to in conjunction with the DMM to trigger the fault trip point. Successful completion of the test would be the isolation of the battery pack or the click of the disconnect relay going to its normally open position. Resetting the entire system to its normal operation mode would follow each test.

What the inspection group would like from each team:

1) A single or multiple sets of test points that give in line access to analog measurement inputs to the BPS. The access point should be ahead of any voltage dividers, filters, or amplification used by the BPS. If not teams should provide proper scalars for test readings.
2) Test point of either screw terminal or of the female banana jack panel type that allow secure points of contact
3) Easy reconfiguration of the test points from monitor only to input only.
4) Labeling and especially polarity indications on all points.
5) Ability to reset system to operational state after each fault condition is initiated
6) Team that are only passively monitoring will need to show labeled meters.
7) Functional and schematic diagram of system
8) Set point values for each fault requirement

Test Equipment

To minimize the complexity and hopefully the time involved with testing the BPS, the following equipment list in **Table 3** will be used during the inspection process to validate each team's system. Teams should come prepared to safely disassemble their battery pack to the module level.

Type	Uses
Digital Multi-Meter(DMM)	Used to measure voltages, small current, and temperature.
Power Supply Voltage reference	Used to produce a floating potential of 0 to the Maximum String Voltage. Lithium battery packs will be tested at the module or cell voltage level. This will allow testing of OV, UV, and OC(shunt or analog sensor).
Thin film heating element w/ PS	Used to produce temperature rise in proximity to BPS thermal sensor to trigger OT condition.
Wire loop and current source	In the case of digital current sensor, it may be necessary for teams to supply a spare sensor that can bypass the actual and be used to produce a trigger condition with a reference current loop.

Table 3 – Test Equipment

Table 4 defines the measured values and the resolution that will be used for testing purposes only. Each team should determine to correct resolution and accuracy for their BPS's optimal performance. Tighter measurement ranges may be implemented depending on battery model and manufacture.

Word	Lithium	Non-Lithium
Voltage	O.01 VDC ± O.01V cell or module(<5VDC) ≈ +10 Bit precision	(10VDC<) 0.1 VDC ± O.1V (<50VDC) ≈ 8 bit (50VDC<) 1 VDC ± 1VDC (<200VDC) same
Current	1 ADC ± 0.2A cell or module ≈ 2%	
Temperature	± 2-degree Celsius	± 2-degree Celsius

Table 4 – Test resolution and precision

Over-Voltage Test

Setup: Each vehicle will be in its operation configuration minus the array at the start of the test.
Vnom = The normal operating voltage at the test point.
Vmin = Manufacture minimum rated voltage for cell or module.
Vmax = Manufacture maximum rated voltage for cell or module.
Vmax_trip = BPS set point to trigger electrical isolation.

1) DMM will be set to auto-range VDC and connected to test points.
2) The first measurement is of the test point voltage as seen at the battery module or cell back to the BPS. Correct battery polarity to be validated for the markings of the test point.
3) Team will then safely isolate sense lead from battery back to isolate test point to provide a reference signal to the BPS.
4) The Voltage Reference positive and negative leads will be connected in parallel to the DMM's test lead.
5) Prior to connecting the sense leads to the test points the Voltage Reference will be adjusted from 0 to Vmax, back to Vmin and set to Vnom as specified by each teams battery manufacture documentation.
6) At Vnom the test leads will be applied to the sense point with correct polarity.
7) The BPS must then be reset and maintain active with the Vnom input.
8) After a period of 10 seconds of no change the voltage reference will be increase to Vmax or Vmax_trip depending on which is less. The rate of voltage change should be resolved at a rate that distinguishes 0.1V changes for string measurements and 0.01V changes for cell or module given the DMM sampling rate.
9) Record the measured trip point at which the relay isolates the battery pack. Teams with passive measurement need only show that they are measuring the same voltage. The actual Vmax or Vmax_trip set point need only be measured at or below the manufacture Vmax to pass. An actual trip point above Vmax requires immediate correction by the team before further BPS inspection. A team may request <u>one additional</u> test for Vmax if they would like to raise their Vmax _trip point.
10) Return reference source to Vnom and have BPS reset to active state.
11) Proceed to Step 1 of Under-Voltage Test next if OV test is passed.

Under-Voltage Test

Setup: Each vehicle will be in its operation configuration minus the array at the start of the test.
Vnom = The normal operating voltage at the test point.
Vmin = Manufacture minimum rated voltage for cell or module.
Vmin_trip = BPS set point to trigger electrical isolation.

1) The BPS must then be reset and maintain active with the Vnom input.
2) After a period of 10 seconds of no change the voltage reference will be decreased to Vmin or Vmin_trip depending on which is greater. The rate of voltage change should be resolved at a rate that distinguishes 0.1V changes for string voltages and 0.01V changes for cell or 3.7V modules given the DMM sampling rate.
3) Record the measured trip point at which the relay isolates the battery pack. The actual Vmin or Vmin_trip set point need only be measured at or above the manufacture Vmin to pass. An actual trip point below Vmin requires immediate correction by the team before further BPS inspection. A team may request <u>one additional</u> test for Vmin if they would like to lower their Vmin _trip point.

Over-Current Test

Setup: Each vehicle will be in its operation configuration minus the array at the start of the test. The OC test will be the most difficult to accommodate due to the various current sensing option available. Two variations of the test will be described. Advance arrangements should be made with the inspection team if none of the proposed tests will work for a team's BPS system.

Imax = Manufacture maximum rated current for cell or module. (Charging / Discharge)
Imax_trip = BPS set point to trigger electrical isolation. (Charging / Discharge)
Vsen_max = BPS shunt voltage scalar corresponding to the Imax or Imax_trip depending on which is lower. (Charging / Discharge)
Iref_max = BPS sensor current scalar corresponding to the Imax or Imax_trip depending on which is lower. (Charging / Discharge)

Analog Shunt or Hall Effect Type Current Sensor

1) With the vehicle shut off the team will isolate positive and negative sense leads from a single battery string shunt or Hall Effect sensor to the test point to provide a reference signal to the BPS.
2) The Voltage Reference positive and negative leads will be connected in parallel to the DMM's test lead.
3) Prior to connecting the sense leads to the test points the Voltage Reference will be adjusted from 0VDC to Vsen_max, back to 0VDC as specified by each teams battery manufacturer's documentation and shunt/hall effect scalar value.
4) At 0VDC the test leads will be applied to the sense point with correct polarity (representing charging or discharging).
5) The BPS must then be reset and maintain active with the 0VDC input.
6) After a period of 10 seconds of no change the voltage reference will be increased to Vsen_max. The rate of voltage change should be resolved at a rate that distinguishes 0.01V changes given the DMM sampling rate.
7) Record the measured trip point at which the relay isolates the battery pack. The actual Imax or Imax_trip set point need only be measured at or below the manufacture Imax to pass. An actual trip point above Imax requires immediate correction by the team before further inspection will occur on the BPS. A team may request one additional test for Imax if they would like to raise their Imax _trip point.
8) Test will be repeated for step 4 through 7 with the sense point polarity reversed to cover charging and discharge limits.

Digital output Current Sensor

In the case of digital current sensor, it may be necessary for teams to supply a spare sensor that can bypass the actual and be used to produce a trigger condition with a reference current loop. Assuming the digital sensor is a closed-loop Hall Effect type a small gauge wire(capable of 10A) would be loop N number of times in order to create N x Iref_max = Imax or Imax_trip.

1) With the vehicle shut off the team will exchange connections with the existing in-line sensor with the reference sensor setup with wire a loop.
2) The leads to the current loop will be connected to a reference current sources that is in series with the DMM's test lead. The DMM will be placed in current mode for 0-10A range.
9) Prior to resetting the BPS the current loop will be adjusted from 0A to Iref_max, back to 0A as specified by each teams battery manufacture documentation and N x Iref_max scalar value (representing charging or discharging).
3) The BPS must then be reset and maintain active with the 0A current loop input.
4) After a period of 10 seconds of no change the current reference will be increased to Iref_max. The rate of current change should be resolved at a rate that distinguishes 0.1A changes given the DMM sampling rate.
5) Record the measured trip point at which the relay isolates the battery pack. The actual Imax or Imax_trip set point need only be measured at or below the manufacture Imax to pass. An actual trip point above Imax requires immediate correction by the team before further

inspection will occur on the BPS. A team may request one additional test for Imax if they would like to raise their Imax _trip point.

6) Test will be repeated for step 4 through 7 with the current loop inputs reversed to cover charging and discharge limits.

Over-Temperature Test

Setup: Each vehicle will be in its operation configuration minus the array at the start of the test. The battery box may require being opened to apply a thin-film heating element and thermocouple in proximity to a BPS temperature sensor prior to test.

Tamb = Ambient pack temperature
Tmax_Charge = Manufacture maximum rated Temperature for cell or module while charging
Tmax_Discharge = Manufacture maximum rated Temperature for cell or module discharging
Tmax_trip_Charge = BPS set point to trigger electrical isolation while charging
Tmax_trip_Discharge = BPS set point to trigger electrical isolation while discharging

1) DMM will be set to temperature readout in Celsius and thermocouple temperature probes added.
2) Prior to adding the temperature probe to the battery pack a test will be preformed to check the ability of the heating element to raise the DMM temperature readout to the Tmax specified by each teams battery manufacture documentation.
3) The temperature probe and thin-film heating element will need to be placed in immediate proximity to one BPS temperature sensor or identical sensor board within the battery pack prior to test. The element may need to be taped in place. If possible the lid should be returned to minimize wind or direct sunlight.
4) The first measurement is of the ambient temperature of the pack at the BPS temperature sensor without the heating element.
5) The BPS must be reset and maintain active with the Tamb input.
6) After a period of 10 seconds of no change the temperature will be raised for the sensor to Tmax_Charge or Tmax_trip_Charge depending on which is less. The rate of temperature change should be resolved at a rate that distinguishes 1-degree Celsius given the DMM sampling rate.
7) Record the measured trip point at which the relay isolates the battery pack. The actual Tmax_Charge or Tmax_trip_Charge set point need only be measured at or below the manufacture Tmax to pass. An actual trip point above Tmax requires immediate correction by the team before further BPS inspection. A team may request one additional test to Tmax if they would like to raise their Tmax _trip point.
8) Test will be repeated for step 5 through 7 with the temperature raised to cover discharge limits at Tmax_Discharge or Tmax_trip_Discharge.

Re-Testing

Re-testing will consist of repeating a subset of the test cases after corrections have been made to correct problems found in previous testing. Re-testing will be considered complete if 1) all test cases that revealed problems in the previous testing have been repeated and the results have met the passing criteria, and 2) all test cases that revealed no problems during the previous testing, but test components that are affected by the corrections, have been repeated and the results have met passing criteria.

Firmware or Physical Lockout

Once the BPS has passed scrutineering teams will need to have a method to prevent any firmware or hardware adjustments to the fault trip point settings. This can include sealing the BPS into the battery box or its own compartment. Teams that seal only their batteries for access within their battery box will require security tape over programming headers or adjustment potentiometer. Any changes to firmware or hardware settings needs to be done under the attention of an inspector or assigned observer. Any necessary changes may require one or all test to be complete again before a team may drive.

Supplemental Battery

As required by the chemistry of the battery type the supplemental will be verified to be protected for conditions under which it will operate on the vehicle. **No Secondary Lithium battery types shall be used for the Supplemental Battery (2016).**

Fault Indication

During testing the required driver and external BPS fault indicators will be observed. The dash indicator for the driver must provide warning of the automatic opening of the Main Power Switch. The external strobe indicator will be verified to activate. Team should make accommodations to demonstrate the strobe works without the body or having cables that can reach temporarily for verifications. A DMM is also available to check circuit activation from the BPS.

BATTERY PROTECTION SYSTEM
OVER VOLTAGE(OV) TEST

☐ String ☐ Module ☐ Cell – Test Level ☐ Pass ☐ Fail

Nominal Voltage: __________ Vnom @ ___ °C **BPS V Resolution:** _______ Bit
Max Voltage: __________ Vmax @ ___ °C **BPS V Range:** _____-_____ VDC
BPS Max Trip: __________ Vmax_trip **BPS Sample Rate:** _______ S/s
☐ Filtering ☐ Delay **BPS Disconnect Delay:** ___ s

Notes: ____
____

BATTERY PROTECTION SYSTEM
UNDER VOLTAGE(UV) TEST

☐ String ☐ Module ☐ Cell – Test Level ☐ Pass ☐ N/A ☐ Fail

Nominal Voltage: ___________ Vnom @ ___ °C **BPS V Resolution:** _______ Bit
Min Voltage: ___________ Vmin @ ___ °C **BPS V Range:** _____-_____ VDC
BPS Min Trip: ___________ Vmin_trip **BPS Sample Rate:** _______ S/s
☐ Filtering ☐ Delay **BPS Disconnect Delay:** ___ s

Notes: ____
____

BATTERY PROTECTION SYSTEM
OVER CURRENT(OC) TEST

☐ String ☐ Module – Test Level ☐ Pass ☐ N/A ☐ Fail

Max Current (charge):_______ Imax @ __°C **BPS I Resolution:** ________ Bit
Max Current (discharge): ______ Imax @ __ °C **BPS I Range:** ______-______ VDC
BPS I Trip: ___________ Imax_trip **BPS Sample Rate:** ________ S/s
☐ Filtering ☐ Delay **BPS Disconnect Delay:** ____ s

Notes: ____
____

BATTERY PROTECTION SYSTEM
OVER TEMPERATURE(OT) TEST

☐ String ☐ Module ☐ Cell – Test Level ☐ Pass ☐ N/A ☐ Fail

(Charge) / (Discharge)
Max Operating Temperature: ____ / _____°C **BPS T Resolution:** ________ Bit
BPS T Trip: ______°C Tmax_trip_charge **BPS T Range:** ______-______ °C
BPS T Trip: ______°C Tmax_trip_discharg **BPS Sample Rate:** _________ S/s
BPS Disconnect Delay: _____ s
Notes: ____