Abstract

This document examines the high-voltage (tractive) and grounded low-voltage systems of the LFEV-ESCM system to prove that they meet Formula Hybrid requirements.
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Executive Summary

Introduction

As a high-energy power system, the LFEV-ESCM contains high-voltage systems that can discharge at currents in excess of 200 amperes. To control this, the high-voltage systems are combined with low-voltage-powered control circuitry. Safety requirements and good engineering practice dictate that high-voltage and low-voltage systems be electrically (galvanically) isolated. This means that the two systems can neither share a current path to ground, nor share a common ground. The analysis presented below shows how the LFEV-ESCM maintains separation between the high-voltage (hereafter HV or tractive) assemblies and the low-voltage (grounded low-voltage or GLV) assemblies.

Additionally, the Formula Hybrid competition imposes energy limits on the accumulator system of the vehicle. A quick analysis proves that the LFEV-ESCM’s energy storage capacity is within these limits.
Requirements Analysis

Voltage and Energy Limits

**EV1.2.4** – The GLV system must be a low-voltage system; see EV1.1.2.

In EV1.1.2, a low-voltage system is defined as less than 30VDC. Our system uses a 24-volt Hengfu power supply to power the GLV system, so this requirement passes.

**EV3.3.3** – Maintenance plugs, additional contactors or similar measures must be taken to allow electrical separation of the internal accumulator segments such that the separated segments contain a maximum voltage of less than 120 VDC fully charged and a maximum energy of less than 12 MJ. The separation must affect both poles of the segment.

Each separated accumulator segment will contain seven 3.2V, 60Ah cells. When fully charged, the cells reach up to 3.4V open-circuit voltage. This means that the maximum voltage of a fully-charged pack is 23.8V, well under the 120VDC requirement.

Also, seven 60Ah cells at 3.4V each, the pack’s stored energy can reach up to 1428Wh, which is 5.14MJ. This is less than the 12MJ requirement and passes, as well.

Galvanic Isolation

**EV3.6.5** – Any GLV connection to the AMS must be galvanically isolated from the HV.

The only GLV connection to the BMS system occurs at the I2C isolator chip, the Analog Devices ADuM1250. This part is UL-rated up to 2500Vrms for 1 minute. It has basic voltage isolation up to 400Vrms and reinforced regulation up to 125Vrms.¹ Since this is the only connection point from the BMS to the GLV system, it passes this requirement.
EV4.1.3 – Traction system and GLV circuits must be physically segregated such that they are not run through the same conduit or connector, except for interlock circuit connections.

Throughout the system, the HV and LV wiring is separated. The only place where it could be argued is in the charging cable (CW0 on the ICD). This contains the charging positive and negative terminals as well as a safety loop dummy connection. Because the safety loop is an LV system and the charging path carries 25A, some might think this is a concern. However, the cable is designed so that connecting the charger automatically breaks the safety loop, so the discharging path can never be closed while the charger is connected. Also, since the maximum pack voltage is under 30VDC (25.2VDC when charging), the charger is technically not a high-voltage system. All other wiring and cabling clearly separates HV and LV wires.

EV4.1.4 – GLV circuits must not be present in the accumulator container except for required purposes, for example the AMS and the AIRs.

The BMS and the AIRs are the only GLV circuits in the accumulator container, so this requirement is passed.

EV4.1.5 – Where both tractive system circuits and GLV circuits are present within an enclosure, they must be separated by insulating barriers made of moisture resistant, UL recognized or equivalent insulating materials rated for 150 C or higher (e.g. Nomex based electrical insulation), or maintain the following spacing through air, or over a surface (similar to those defined in UL1741): U < 100 VDC: 1 cm (0.4 inch)

This requirement fails on the BMS board but passes on the Load Controller PCB. This has been proven by inspection on the ATR.
EV4.6.4 – The tractive and GLV systems must be galvanically isolated.

Two points of connection between the tractive and GLV systems exist. One is between the BMS and the high-current path in the pack. As discussed, the BMS is specifically exempt from this requirement. To show that the BMS’ connection to the pack is safe, we analyze the circuit in Figure 1, shown below.

Figure 1 – The current path across the terminals of a cell, through the BMS and through the cell

An open-circuit resistance measurement of the BMS taken at its voltage measuring points yields about 8 kΩ. Since the cell’s open-circuit resistance is 2 mΩ, less than one one-millionth of the current through the high-current path flows through the low-current path. Given a short-circuit current draw of about 1000 A, this means that less than 1 mA would go through the BMS board. All on-board components are rated up to this rating, and indeed, the board draws a higher current than this for its normal operation (around 20 mA).

The second place of HV/LV connection is the Load Controller. To ensure that separation is maintained, a Bender IR155-3210 Insulation Monitoring Device (IMD) is installed in the Load Controller. Test points from both the tractive and GLV systems connect to this device, which uses a test resistance and current pulses to ensure that the two systems remain separated. Because the competition requires the use of this device, its connection between HV and LV systems is not concerning. Its internal resistance, as rated by the manufacturer, is above 1.2 MΩ, so even if the pack short-circuits across this connection, less than 1 mA would flow.
Voltage Indicators

**EV3.3.8** – The accumulator voltage indicator must be directly controlled by voltage being present at the connectors using hard-wired electronics. (No software control is permitted). Activating the indicator with the control signal which closes the AIRs is not sufficient.

The accumulator voltage indicator was not included in the system, and thus this requirement fails.

**EV4.11.4** – The TSAL must not be powered by high voltage.

**EV4.11.5** – The TSAL must be directly controlled by voltage being present at the output of the accumulator and powered by the GLV system (no software control is permitted). Activating the indicator with the control signal which closes the AIRs is not sufficient.

The Tractive System Active Light (TSAL) shows when voltage is being applied on the pack side of the isolation relays between the pack and the load. The diagram below shows that the TSAL turns on if full system voltage is applied or if the AIRs are closed.

![Figure 2 – Diagram of the TSAL PCB in the Load Controller](image)
If HV is present on J1, the light (the diode in the middle of the diagram) is powered and turns on. Also, if the control signal to close the AIRs (on J3) is on, this will turn the switch that will also turn on the LED. The switch is an optoisolated switch, thus maintaining separation between the GLV and tractive systems.

**Current Paths**

| EV4.6.9 | Only intentional current paths may be used. Steel may not be used as part of the current path. No plastic in the terminal stack-up. |

All high-current paths flow through aluminum bars or copper wiring. Some steel bolts are used to fasten aluminum bars together, and during testing it was observed that one bolt (connecting the RelaySideJumper pieces) heated in excess of 60°C when discharging at 360A. Unfortunately, it was too late in the project to properly analyze this joint to see how much current passed through it. There is a similar joint on the other end of the pack connecting a cell terminal to the discharging fuse; it is recommended, in future implementations of the Battery Pack, that the RelaySideJumper with the steel bolt be replaced with a press-fitted bar like the one on the opposite side of the pack to avoid this heating issue.
Appendix A: References

1. Analog Devices ADuM1250, Hot-Swappable Dual I2C Isolator, datasheet: