2009 FORMULA HYBRID ELECTRICAL SAFETY RULE NOTES

Introduction

This document provides further clarifications on the reasons for the Formula Hybrid rules, and guidance how to satisfy the intent of the rules. The rules themselves establish the official requirements, but this document will help you understand them and help you avoid missing aspects of them—a single sentence in the rules sometimes requires a lot of different things on the car itself.

4.1 High-Voltage Isolation

Isolation is one approach to making a safe high-voltage system. It's not the only approach—for example power systems in North America and many other places are ordinarily grounded rather than being isolated—but it's a good one to use for vehicles, and is mandated for Formula Hybrid. The idea is that if a person were to inadvertently contact one node in the high voltage system and any other point on the car (including any node in the low-voltage system), no injury would result, because there would not be a complete circuit.

Because the high-voltage system is floating relative to the car's frame, all nodes in the high voltage system are equally dangerous. If node A of a 300 V high-voltage system is called "0 V" and node B is called "300 V," it might seem like the isolation requirements for node A are less stringent than the requirements for node B. But we could equally well call node A "-300 V" and node B "0 V" without any physical change to the system. Both need to be treated as dangerous and both need to be safely isolated.

Circuit considerations

Safely isolating circuits means, first, not having any electrical connection between the high-voltage and low-voltage systems. However, there are often requirements for sending signals between low-voltage and high-voltage systems, for monitoring and control. For example, there is often a need to monitor voltages (e.g., the accumulator voltage, total and/or cell-by-cell) or currents. And there is typically a need to send a signals from driver controls to a motor controller, and perhaps other systems as well. Ways of isolating these signals include:

- **Optocouplers** (also called opto-isolators), are typically designed to isolate digital signals. For analog signals, one can use a slightly more complex circuit with special optocouplers designed for that application, such as the Avago HCNR200 series. However, an isolation amplifier can be simpler to use.
- **Isolation Amplifiers** are complete modules that use an optocoupler, transformer, or other isolation device to send signals across an isolation barrier and provide a simple analog voltage as the input and as the output. Avago HCPL-7800 series and HCPL-7500 series and Texas Instruments' ISO124 are some low-cost options in integrated circuit packages; they require power supplies on both sides of the isolation barrier. Analog Devices makes larger modules (e.g. AD202, AD204, etc.) that require power from only one side. Other manufacturers include LEM and Dataforth.
- **Electromechanical solutions** include relays and servo motors controlling potentiometers. In the case of a servo controlled pot, note that most pots are not designed for high voltage between the electrical terminals and the metallic mechanical parts, so isolated mounting will typically be required.
- **Transformers** can be used to isolate ac power or signals, but not dc signals.
- **Isolated dc-to-dc converters** can transfer power across an isolation barrier, and can also change voltage levels. For example, you might want to supply a low-voltage control and instrumentation system with power derived from the high-voltage system. Note that many dc-to-dc converters are not isolated. Those

that are isolated will say so in the specifications, and will also carry a voltage rating for that isolation (which should be higher than the highest peak voltage expected in your system, typically with a good safety margin).

- **Optical data links** using optical fibers are the ideal way to communicate signals between low-voltage and high voltage systems.
- **Video isolation.** A video camera pointed at a meter that is connected to the HV system can provide a safely isolated signal that can go to a dashboard display.

Note that there may be systems that run on low voltage, but are considered to be part of the high-voltage system because they are directly connected to the high-voltage system without isolation. That's acceptable, as long as every component and wire that is connected to these systems without isolation is treated as part of the high voltage system: run through orange conduit, kept out of the cockpit, etc.

Construction considerations: Physical Segregation

Ideally, there would be separate high-voltage boxes and low voltage boxes with no mixing of the two, and no chance of an inadvertent connection. However, where the high-voltage and low-voltage systems interface, there will be boxes that contain both. Any such box ***must*** be divided into clearly defined low-voltage and high-voltage regions. High voltage wires and low voltage wires, even though they are insulated, must be kept apart from each other and confined to their respective regions of the box. The regions of the box should be divided by a robust UL recognized insulating barrier such as Nomex or Formex as specified in the rules.

The reason for this is that many simple faults can cause a short: insulation on a wire might fail due to vibration, overheating, or a crash, or a wire termination might come loose. If one of these faults causes a short within the high-voltage system, the system will fail, but no shock hazard will result. Similarly, a short within the low-voltage system could cause a system failure, but won't result in a shock hazard. Keeping the wiring segregated ensures that any shorts stay within the respective systems.

The only thing that may bridge between these regions of a box is an isolation devices, as listed above.

Special note: Accumulator Enclosures

The accumulator box is an especially critical region, because the high-voltage power within it remains live even when the system is de-energized. For this reason no circuits, low voltage or high voltage, should be located within the accumulator box unless there is a specific need for them to be there, such as:

- Cell-by-cell voltage and temperature monitoring systems.
- Indicator circuit and isolation relay (as specified by 4.6).

The design and construction of those circuits must strictly follow the rules for isolation, physical segregation, and fusing (for example, there must be barriers between high-voltage wiring and the low-voltage control wires going to the relays). And the portion of the system located within the accumulator box must be minimized. For example, a cell-by-cell monitoring system would typically have isolated data acquisition in the accumulator box, communicating (ideally via an optical data link) to a monitoring and display system located outside the box.

Locating other equipment, such as a motor controller, outside the accumulator box is important for many reasons, including that fact that it is then possible to open the cover to the motor controller and work on it with the system de-energized, and thus have no exposed high voltage.

Common problems: throttle pots and voltage meters.

Some places where it is tempting to violate these rules include throttle pots on some motor controllers and dashboard voltage displays.

Some motor controllers are intended for a negative ground system rather than an fully floating high-voltage system, as is used in Formula Hybrid. Some of these are intended to be controlled by a pot connected to terminals which are not isolated from the high-voltage system. According to Formula Hybrid rules, these connections are considered to be part of the high-voltage system, and are not allowed to connect to driver controls (4.2). Possible solutions include the following:

- Use a motor controller with isolated connections to the throttle pot. Some spec. sheets are not clear about whether the throttle pot is isolated, so verify this with the manufacturer and bring documentation to prove it. If you claim that throttle pot connections are isolated and we don't have documentation, you may not be allowed to compete, or we may perform a hi-pot test on the controller, a test that can be destructive if it is not in fact isolated.
- Use a servo motor to control the pot, with this assembly mounted in an enclosure with high-voltage and low-voltage wiring properly segregated, and with metallic parts of the pot body isolated from the low-voltage circuitry. The construction of such a solution should be robust, as a failure that leaves the control set to full power would require prompt driver action to shut off power.
- Use a "digital potentiometer" from Analog Devices, for example, with a control signal run through a signal isolator of one of the types listed under "Circuit Considerations".

If you intend to use a different solution, we suggest requesting that a Formula Hybrid technical examiner review it prior to the event.

Voltage meters cannot be connected to the HV system without incorporating isolation. The only exception to this would be meters outside the cockpit area that are inside HV enclosures (which would need to be transparent for the meter to be useful). If you show up with a meter connected without isolation, you will be required to remove it and run without the benefit of that meter. Voltage dividers may lower the voltage to safe level, but recall that no voltage within the HV system is considered safe, so the reduction in voltage provided by a voltage divider is irrelevant.

4.2 No Exposed Connections

Some equipment used by many Formula Hybrid teams, such as some motors and motor controllers, is intended to be mounted inside an enclosure, and has exposed connections. When it is mounted on a open frame, these connections can violate the rules. These connections must be enclosed. The enclosure may fully cover the equipment or may just cover all the connections, or each connection may have its own connection. 12-V battery boots are not intended to safely isolate high-voltage systems on a race car and are not adequate protection; they also don't provide anchoring for conduit. A simple plastic box mounted over a terminal can suffice, as shown in Fig. 1.

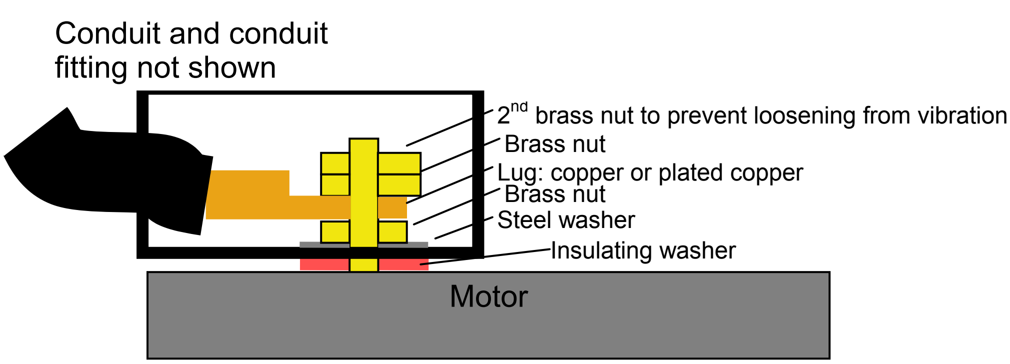

Fig. 1. Motor terminal cover.

Another key provision in this rule prohibits "HV connections behind the instrument panel or any cockpit switch or control panels." No HV should be in the cockpit at all—the rule only mentions controls and switches because those were the only plausible reasons for having HV in the cockpit.

4.3 HV Insulation, Wiring and Conduit

It can be tempting to use any non-metallic material found around the shop for insulation. That's against the rules for good reason: it may not be as good an insulator as it looks, it may melt at a temperature near normal operating temperature, and it may burn easily. One team reported tracing a ground fault to a piece of rubber hose used as an insulator. The rubber had carbon black in it and was sufficiently conductive to cause a fault (and could have also caused a lethal hazard). Insulation materials must be documented.

Strain relief is the practice of mechanically securing the end of a wire or cable separately from the electrical connection. This improves reliability by avoiding mechanically stressing the electrical connection. Not only does it make it less likely for a wire to break off, but if a wire or connection were to come loose, it prevents the live end of the wire from coming loose and becoming a hazard. In most cases in Formula Hybrid, strain relief is accomplished by mechanically anchoring the ends of the conduit, through the use of conduit fittings. A good article on selection of conduit and fittings is

> "Guide to Nonmetallic Conduit Applications: An Application Guide to Nonmetallic Conduit, Tubing and Fittings," by Craig Yoss, Electrical Contracting Products Magazine, March 2006.
> http://www.ecpzone.com/print/ECP-Magazine/Guide-to-Nonmetallic-Conduit-Applications/1$1459

For low-voltage wiring, strain relief is not as critical a safety issue, but it is still important for both reliability and safety: shorts in the low-voltage system can create fire hazards which must be taken seriously on a vehicle with flammable fuel and accumulators. Strain relief can be accomplished with various clamps which may be integrated into electrical connectors or boxes or mounted in ports of boxes, or it can be as simple as anchoring the wire with a nylon wire tie to a secure mounting point.

A related issue is ensuring that wire insulation is not chafed or cut by edges of enclosures or the like. The worst scenario is a hole cut in sheet metal for a wire to go through; the sharp edge of the metal cuts the insulation and creates a short circuit. Strain relief clamps fitted in a hole in a metal enclosure, or conduit fittings, normally take care of this problem, but when strain relief is provided my other means, a grommet inside the hole will be needed to protect insulation from the edges of the hole.

External heat sinks are required to be grounded to the frame of the car, because an insulation failure or a loose wire could otherwise make the heat sink become live. The same goes for any other piece of metal exposed metal. For example, a metal screw used to mount something inside a plastic box could become live if a loose wire contacted it. Electrical enclosures meant for high-voltage use, such as non-metallic NEMA enclosures, have internal mounting points which can be used without having screws penetrate the enclosure. Other ways to address this issue include:

- Using plastic screws for any screws that penetrate a high-voltage enclosure.
- Securely covering any metal screws that penetrate a high-voltage enclosure with an insulator, on the inside, on the outside, or both.
- Using a metallic enclosure, grounded to the frame.
- Individually grounding any screws that penetrate the enclosure.
- Adding an internal base plate for mounting without having the mounting screws penetrate the enclosure.

Any exposed metal or other conductor (e.g., carbon fiber) on the car should be grounded to the frame—for example a metal or carbon-fiber body panel should have electrical continuity to the frame, to ensure that it cannot become live.

Internal heat sinks are not required by the rules to be grounded. But it's a good idea to ground them anyway: someone working on the system might assume that a large piece of metal was grounded and thus safe to touch. If they are not grounded, a high-voltage warning label should be on the heat sink.

4.4 Fusing

See the separate fusing tutorial for more detail on this very important topic. A few key points are:

- Low- and high-voltage systems must both have proper fusing, located as close as possible to the energy source.
- Fuse current ratings must be no greater than the current rating of the smallest wire in the system they protect.
- Fuses used for dc must be rated for dc, and must carry a dc rating equal to or greater than the system voltage. Putting lower-voltage fuses in series does not allow using fuses with a lower voltage rating.

4.9 Charging Equipment

Some changes and notable items on charging equipment:

1) Charging equipment is required to be **UL listed**. This guarantees a minimum level of safe design and construction, including isolation between the line voltage (which is ground referenced) and the vehicle HV system (which is isolated). Some popular high-power electric vehicle chargers are not isolated, are not UL listed, and are not allowed at Formula Hybrid events.
2) "**All charging equipment must be maintained in safe working condition**." Some particular items of concern here:
    - High-voltage input or output terminals must be covered.
    - Input and output cables must have adequate strain relief.
    - Ground connections on the input must be maintained in good condition; extension cords used must have intact ground connections.
3) "**The vehicle must be de-energized while charging from external sources (as much as possible while still allowing charging), and no other activities (including any mechanical or electrical work) shall be allowed.**" This is a new requirement.

6.10.4 [Electrical Work During] Fueling and Refueling

This new rule is not in the electrical section but affects electrical work: "The vehicle must be de-energized when refueling, and no other activities (including any mechanical or electrical work) shall be allowed while refueling. "

7 Required Equipment

Required safety equipment must be kept where it can be immediately and easily located. Insulating gloves are intended to serve as liners be used with leather protectors; teams should have the full set including the leather protectors. Note that simply wearing gloves is rarely adequate for working with live HV systems—they should be available as extra protection or emergency use, and are not intended as a way avoid following other safety precautions.