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Safety System of an Electric Vehicle for Formula Racing

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***Abstract*—Developing an Electric Formula car has its own challenges associated with it, perhaps what convol utes the case is the proper safety measures that needs to be in place to ensure the well being of the driver. A formula car must perform well as to achieve extremely high speed in a really small time frame, and also keep a tab on proper working of all the components which otherwise could be catastrophic. While Mechanical parts have their own safety standards and measures in place, electrical parts and safety designing should follow the stringent rules of FSAE. The paper discusses an innovative way in which safety systems of a highly safe Formula electric vehicle was achieved by Analog circuits designing and Electronic Control Unit (ECU) programming, taking into consideration different possibilities and at the same time conforming to the uncompromising rules of FSAE.**

***Keywords*— ECU, FSAE, Safety Systems**

I. INTRODUCTION

Every car, no matter what class it comes under, has safety as its top priority. This paper emphasizes on different safety measures taken to ensure proper functioning of electrical components. This is a huge task because a plethora of possible faults that needs attention and act in time accordingly. To achieve a safe car, a failure mode effect analysis was performed that jotted down the possible failure modes of the car. Based on the analysis, several circuits were designed that was ultimately integrated into one single circuit board. To complement the board, the ECU of the car was developed to work alongside.

After optimization, a final design was contrived, which will be discussed in the upcoming topics. The paper begins with a system overview that is later discussed in detail. Finally, the results are examined and explained. The above circuits were developed for the Formula Electric Car that was developed by Team Ojas of Vellore Institute of Technology, Vellore for the 2014 season.

II. SYSTEM OVERVIEW

The vehicle uses two Agni 95-R Permanent Magnet Direct Current (PMDC) motors that is powered by two Li-Po battery packs that are electrically connected in series. The electrical safety of the vehicle is ensured by the Shutdown system that disconnects the battery pack from rest of the tractive system in case of any fault, by disconnecting the Accumulator Isolation Relays (AIRs). In case of emergency,three shutdown buttons are provided, onein cockpit and two on both the sides of the vehicle that completely de-energize the tractive system.

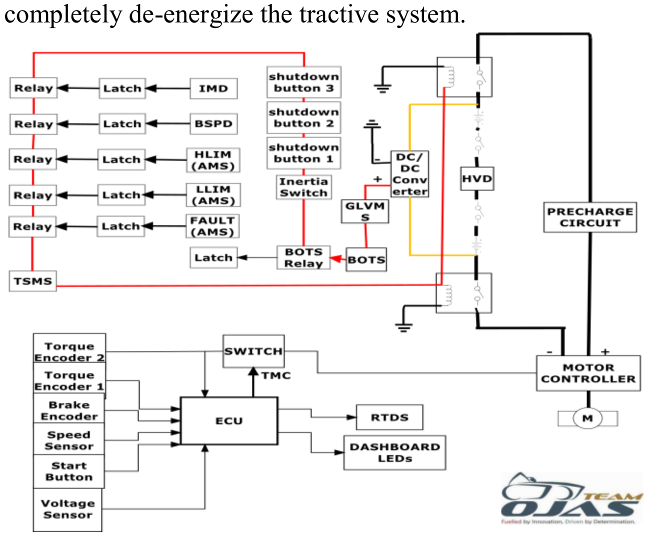


Fig. 1. Shutdown System Block Diagram

Fig. 1 describes the overall arrangement of the circuits. The shutdown circuit is installed to ensure the safety of the vehicle as well as of the driver. It consists of various monitoring devices, systems and switches, which disconnect the batteries and motor controller in case of any fault thus, completely shutting off the vehicle. The circuit has been strategically designed keeping in mind all possible conditions, which may occur.

The LV system is powered by the DC/DC converter, which takes supply from the HV batteries. The two master switches, Ground low Voltage Master Switch (GLVMS) and Tractive System Master Switch (TSMS), are connected in a way that upon disconnecting them, TSMS will power down the entire Tractive System, keeping Low Voltage alive, whereas GLVMS will power down the entire car.

The biggest highlight of the design is that all the controlling elements of the shutdown circuit that includes Brake System Plausibility Device (BSPD), Insulation

Monitoring Device (IMD) latch, Battery Management r Travel Switch (BOTS) latch are designed to be integrated in only one board. Upon detection of fault, a level triggered latch is activated that disconnects the shutdown circuit through a relay that in turn opens the Accumulator Isolation Relays (AIR). This action results in both the battery packs being isolated from the entire system. Inertia Switch and three Shutdown Buttons are connected in series such that upon triggering, they will directly open the AIRs.

To enhance the safety, ECU controls the connection between throttle sensor and motor controller. ECU checks for soft faults in pedal encoders. It also runs the “Ready to Drive” Protocol to start the car every time. This is a safeguard against potential faults while starting the car.

III. Vehicle Safety System Design

A. Shutdown Circuit Board

The Shutdown Circuit Board features some of the most important components that controls the AIRs. These include a BSPD circuit and all the important latches that trigger a local relay, which is connected in series with the AIRs. Important elements of the board are discussed below.

a) BSPD

The safety system of vehicle provides high-level security to battery and driver. In case of any dangerous situation, safety circuit isolates tractive system from battery. This eliminates any post short circuitry and it’s effects.

BSPD takes input from brake pedal sensor and current sensor and compares it with a pre-defined threshold value. If the two values are simultaneously higher than threshold values then a RC timing circuit, set for 0.5 second, gets triggered. This makes sure that if the fault condition persists for 0.5 second, then BSPD latches the fault that opens a local relay connected to the AIRs, that in turn shutdowns power of entire vehicle.Upon proper tuning, threshold value for current sensor comparator is set at 0.38V and brake encoder comparator is set at 2V that illustrates 5kW of power delivered to the motors and sensing hard brake at the same time.

BSPD preserves motor lifetime and also increases running time of battery. Fig. 2 depicts the circuit configuration of BSPD circuit on the shutdown circuit.

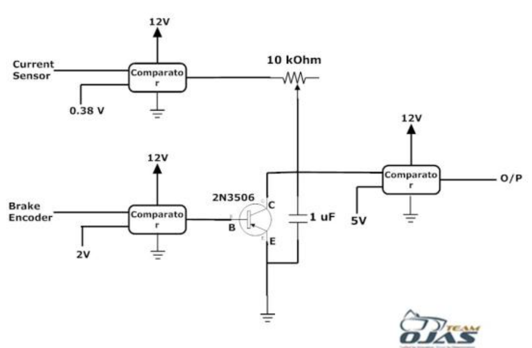


Fig. 2. BSPD Circuit Diagram

System (BMS) latch and Brake Ove Table I represents different BSPD failure modes and its detection.

TABLE I. BSPD Failure Modes

Failure Type	Failure Parameters	Correction or Detection
Brake pedal damaged or lost connection	Ambient voltage at signal output	Pull up resistors ensure fault is detected by ECU and shown on LCD
Current sensor damaged or lost connection	Ambient voltage at sensor output	Pull up resistor ensures BSPD action.
BSPD loses power	Latch will not get switched on	NO type relay ensures shutdown in power cut.

b) Latching

The faults that may occur in the vehicle may be momentary and hence must be latched. For this purpose, an efficient latching system using thyristors(SCR’s-2P4M) has been designed. AnSilicon Controlled Rectifier (SCR) is a gate controlled diode, which can be turned on(active state) by injecting a small trigger pulse of current (not a continuous current) into the Gate, (G) terminal, when the thyristor is in its forward direction. The Anode, (A) is positive with respect to the Cathode, (K), for regenerative latching to occur.

In the case of the BMS, the latches are directly fed by the BMS fault signals (a high pulse in the case of Fault, HLIM, LLIM). Similar configuration has been imitated for BSPD latch. While in the case of the IMD and BOTS, the faults are active low, and hence the input to the latch is fed through an inverting circuit.

All the latches are reset in the same fashion, by means of a reset button for each fault. The thyristors are reset by momentarily applying a ground potential to the SCR. This restores the latch to its initial(inactive) state.

One advantage of using thyristor latches is that they are Electrically Robust, as the lock-on mechanism ensures that at no time can it ever be anywhere between fully on, and fully off. This guarantees that it behaves as an almost Perfect Switch, with very low Power Dissipation in either state. This also confers the ability to
handle Enormous currents in the ON state. A thyristor has a very efficient electronic switch in the range of at least 200 to 6500 volts and 40 to 5000 amps for a single component.

B. Electronic Control Unit

ARM cortex M3 based microprocessor, 67 MHz fast PSoC microcontroller monitors Voltage Sensor, Brake Encoder and two Torque Encoders. ECU controls vehicle’s initiation process in which a proper procedure is followed to check if accelerator, brake and AIRs are in the required state ensuring safety.

To interpret exact accelerator pedal position, two physically different torque encoders are installed. These encoders are position based angular potentiometers. They provide relative reference value with respect to one another to ECU for further signal processing. The ECU checks for any faults in the AIRs before starting the car. This involves a Ready to Drive Procedure check by the ECU.

Figure. 3 diagrammatically represent ECU connections.

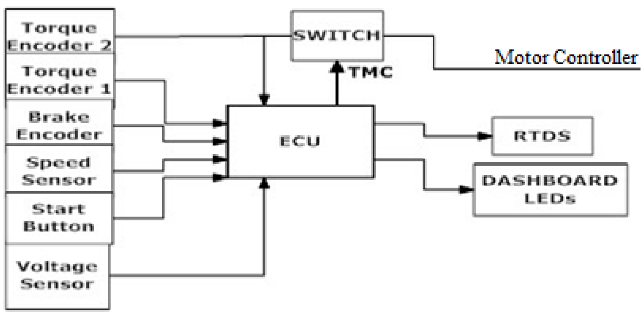


Fig. 3. ECU connectivity block diagram

Table II portrays the steps involved along with its significance.

TABLE II. READY TO DRIVE PROCEDURE

Steps	Output Stage	Significance
Check whether AIRs are closed via voltage sensor	Proceed to check for driver input	Batteries are ready to supply power and all systems are functioning properly.
Ensure hard braking and start button pressed, and Accelerator pedal is not pressed	If no fault in shutdown circuit, Indicate success by buzzer	Brake should be pressed to avoid jerk and driver uses the start button.
Connect throttle to motor controller	Car ready to drive	The car will accelerate if throttle is pressed.

Table III lists the different failure modes related to ECU and its detection.

TABLE III. ECU FAILURE MODES

Failure Type	Failure Parameters	Correction or Detection
Incorrect orientation of throttle sensors	Difference of 10% or more in throttle sensor values	Failure detected by ECU and throttle sensor to motor controller disconnection.
Physical Damage to sensors	Pedal position cannot be determined	
Signal connection of either sensor damaged	Difference of 10% or more in sensor values	
Brake and Throttle Sensors actuated together	Brake Actuation: 10% Throttle Actuation: 25%	Failure detected by ECU and rectified only if the brake is released and throttle actuation goes below 5%
Sensors or signal wires short or open circuited	Open Circuit: ambient voltages Short Circuit: 5 Volts	Detected by the ECU. Pull up resistors used to detect Open Circuit.

C. BMS

Li-polymer battery is the only energy source of vehicle's tractive system and low voltage system. The battery is nothing but a giant capacitor, capable enough to cause fatal injuries to driver if not handled properly.ElithionLithiumate Pro BMS monitors internal battery parameters such as cell temperature and voltage and isolates the entire tractive system from batteries if there is any fault, by opening BMS relay. As battery security is of highest priority, any fault produced by BMS is stored in latch as memory element till it is removed manually. To achieve this purpose, BMS latch is powered up by separate battery.

BMS detects and signals three type of faults, which triggers interlocks in the shutdown circuit thus, completely de-energizing the tractive system. They are: -

- HLIM (Over voltage fault)
- LLIM (Under voltage fault)
- Fault (Over temperature, Under temperature and Cell communication loss)

Table IV delineates different types of BMS failure modes and its detection associated with it.

TABLE IV. BMS FAILURE MODES

Failure Type	Failure Parameters	Correction or Detection
BMS detects a problem in temperature or cell voltage in the cell	Gives a logic low on Fault output pin	Dedicated latch for BMS is triggered and shutdown circuit is opened.
Overcharging of the battery is detected	Gives a logic low on HLIM output pin	Dedicated latch for BMS is triggered and shutdown circuit is opened.
Damage to internal signal wires or sensors	The BMS switches off and shows error message	The latch is triggered and shutdown circuit is opened.

D. IMD

Bender A-ISOMETER® iso-F1 IR155-3203/-3204 approved and certified IMD for automotive purpose is used in the vehicle for monitoring the insulation resistance between the high voltage tractive system and the low voltage system. When the minimum insulation of 100 kΩ exceeds between the HV and LV system, the OKHS of the IMD connected to IMD latch triggers the shutdown circuit resulting in the shutdown of the system. A red indicator LED mounted in the cockpit reflects the status of the IMD. There is a huge advantage in using the Bender IMD as its technology allows it to signal insulation faults even under high system interferences which may be caused by motor control processes, accelerating, energy recovering etc.

Insulation is of highest priority. Insulation loss is fatal for both the driver and vehicle. Hence, IMD latch can store fault state till it is reset manually.

Fig. 4 is a diagrammatic representation of IMD connection.

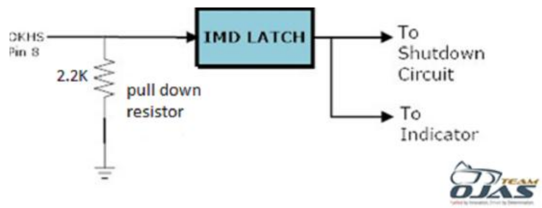


Fig. 4. IMD connectivity

Table V points out the IMD failure modes and its detection.

TABLE V. IMD FAILURE MODES

Failure Type	Failure Parameters	Correction or Detection
IMD detects loss of insulation	IMD drives latch input low	Dedicated IMD latch is triggered and remains so till fault is cleared
IMD loses connection to HV+, HV- or reference GND	IMD drives latch input low	Dedicated IMD latch is triggered and remains so till fault is cleared
IMD loses connection to latch	Ambient voltage at latch input	Pull down resistor ensures that latch input drives low and latch triggers

E. *Pre – Charge Circuit*

A circuit that is able to pre-charge the intermediate circuit to at least 90% of the current accumulator voltage before closing the second AIR is implemented. Pre-charge circuit is shown in Fig. 5.

Pre-charge circuit limits the high inrush current when motor controller is connected to the batteries. Otherwise high inrush current can severely damage the capacitors in the motor controller.

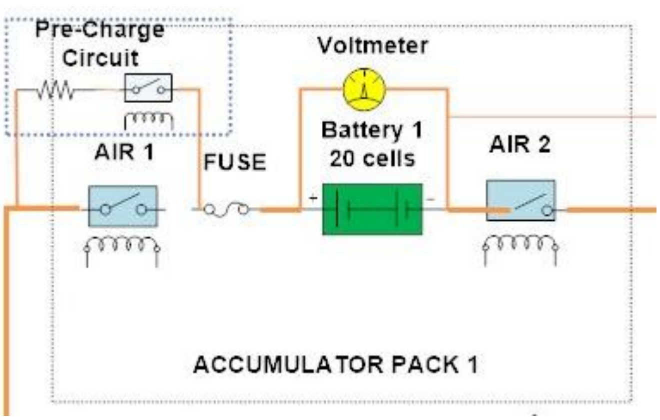


Fig. 5. Pre-Charge Circuit Diagram

Fig. 6 shows simulation result of pre-charge circuit. It can be seen that motor controller capacitor is charged to 90% in 2.5 sec.

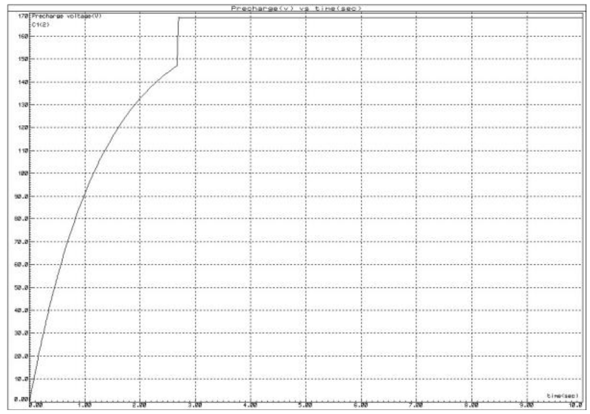


Fig. 6. Pre-Charge Circuit Simulation

F. *Discharge circuit*

Even if the AIRs are disconnected it is not necessary that the tractive system voltage is reduced, because the capacitors of the motor controller are still charged. To overcome this problem, the discharge circuit is designed. It will simply short-circuit the motor controller terminals via a suitable resistor. A discharge circuit consists of a discharge resistor and a NO(Normally Open) relay. It is electrically connected between motor controller terminals. Fig. 7 shows the discharge circuit diagram and its connections.

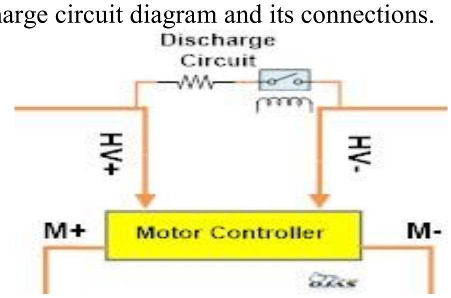


Fig. 7. Discharge Circuit Diagram

Fig. 8 shows simulation result of discharge circuit. Discharging of motor controller capacitor is discharged by 50% in 5sec.

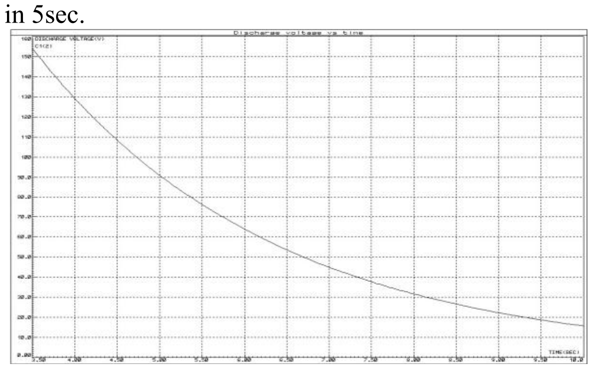


Fig. 8. Discharge Circuit Simulation

G. Inertia Switch

A Sensata resettable crash sensor is mechanically attached to the vehicle to ensure the safety of driver and to reduce the risk of fire and electrical shock in post-crash situations.The Switch is connected in series with the shutdown buttons such that it triggers the shutdown circuit leading to opening ofthe AIRs when the impact load decelerates the vehicle at between 6g for 50ms and 11g for 15ms is applied on the vehicle.

TableVI illustrates different failure modes of inertia switch

TABLE VI. INERTIA SWITCH FAILURE MODES

Failure Type	Failure Parameters	Correction and Detection
Car crashes	Inertia Switch triggered due to vibrations	Shutdown circuit is opened

H. Brake-Over-Travel-Switch

A Mechanical single pole, single throw switch is used as a brake over travel switch and is installed in series with the shutdown circuit.It detects brake system failure in which the brake pedal over travels and makes sure that the shutdown circuit opens the AIRs.

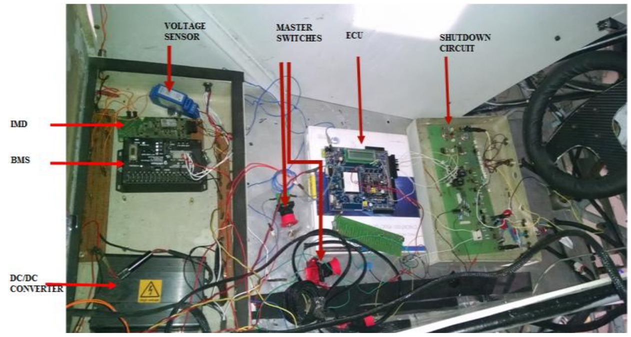
TABLE VII lists failure modes of BOTS.

TABLE VII. BRAKE OVER TRAVEL SWITCH FAILURE MODES

Failure Type	Failure Parameters	Correction or Detection
Cables to or from BOTS are damaged	Continuity in shutdown circuit is broken	AIRs are opened as shutdown circuit is opened
Switch is damaged and does not switch	Over actuation of brake will not open the shutdown circuit	Driver can detect the fault through a LED on the dashboard.

I. Shutdown buttons

There are 3 shutdown buttons installed on the vehicle for emergency purposes. Pressing any one results in opening the shutdown circuit. Two shutdown buttons are located on either side of the vehicle on the main hoop at approximately the level of the driver's shoulders. The third button serves as a cockpit mounted master switch and is located within easy reach of the belted-in driver, alongside the steering wheel, and unobstructed by the steering wheel or any other part of the car.



There areinternational electrical symbols consisting of a red spark on a white-edged blue triangle affixed in close proximity to these buttons. Table VIII represents failure modes related to shutdown buttons.

TABLE VIII. SHUTDOWN BUTTONS FAILURE MODES

Failure Type	Failure Parameters	Correction or Detection
Electrical connections are damaged	Continuity in shutdown circuit is broken	AIRs are opened as shutdown circuit is opened
Button is damaged and does not work	Emergency actuation will not shut the car	3 shutdown buttons provided as a contingency

J. Master Switches

The vehicle is equipped with two Master switches, the Grounded Low Voltage Master Switch (GLVMS) and the Tractive System Master Switch (TSMS).The GLVMS, which is located on the right side of the vehicle on the main hoop at the driver's shoulder height, disables power to the GLV system and tractive system when rotated .Similarly, the TSMS, whichis mounted next to GLVMS, disables only tractive system of the car.

Both switches are fitted with a "lockout/tagout" capability to prevent accidental activation of the respective systems. The ON state of both switches is in the horizontal position, which signs the user if vehicle is safe to operate or not.

IV. CONCLUSION

Multiple simulation and testing results highlight that a full proof safety system for entire formula vehicle has been designed. The BSPD, BMS, IMD, pre-charge and discharge circuitry ensures that vehicular components are working properly. And if there is any fault, it is ensured that system indicates it on dashboard. ECU makes sure that only true value is forwarded to motor controller.

Furthermore use of pull-up resistors and NO type relay in design make sure that, the vehicle and the driver are safe even in case of system failure. Entire safety circuit resides on a single printed circuit board, which has reduced wiring problem to none. The safety system design provides simple yet effective debugging platform for users.

Fig. 9. Hardware setup of final prototype

V. FUTURE SCOPE

Although a prototype vehicle is functionally complete and initial testing done, there is always a scope for potential improvement in several areas. From the analysis of initial test runs, it was found that precise diagnosis of faults that occurred due to motors or batteries is difficult. An efficient solution to this is data logging. The data from the BMS indicating cell voltages temperatures, as well as fault signals from the motor controller can be logged during dynamic runs of the vehicle.

An additional level of safety may be included, making it possible to turn off the vehicle through a wireless system. This is possible by a GSM modular system (transmitter + receiver), which upon activation would trigger a relay in the car, thus opening the shutdown circuit and ensuring the safety of the driver and vehicle. This system will completely eliminate the chances of any possible fire hazards or explosions, provided there is a timely activation of the GSM transmitter.

Acknowledgment

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