5. Design Analysis of Formula SAE Electric Vehicle Integrated with Battery Management and Protection Systems

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Abstract

The Formula Society of Automotive Engineers (FSAE) competition for electric vehicle challenges to conduct research in the design of a safe and reliable electric powertrain because of the growing reality of electric mobility due to increase in the demand and cost of conventional energy source and environmental effect of internal combustion engine. There are various aspects in the design of formula electric vehicle such as powertrain design, energy storage, instrumentation and aerodynamics. The vehicle is powered by Li-polymer accumulator equipped with battery management system to monitor state of health (SOH), voltage, state of charge (SOC), temperature and perform cell balancing. The foremost concern is the electrical safety which is ensured by protections systems such as shutdown system, accumulator isolation relays and insulation monitoring device incorporated for the continuous and safe operation of the vehicle. This paper primarily focuses on the protection devices, sensors and interlocks, designed according to the FSAE rules to provide protection to the tractive system of electric vehicle and minimize the severity and likelihood of any hazard during the handling, acceleration and braking action of the vehicle. The feasibility analysis of total supplied power by accumulator pack for the propulsion of electric powertrain was evaluated and recorded which concludes the viable and safe operation of electrical system of the vehicle.

Keywords: *Formula Electric Vehicle; Battery Management System; Electrical Protections; Shutdown Circuitry; Powertrain; Tractive System*

1. Introduction

The Formula SAE (FSAE) is a design competition for students from all over the world which is organized by Society of Automotive Engineers (SAE International) that challenges to conduct research in order to design, manufacture, develop and compete with small, formula style, prototype vehicle according to the FSAE rules and goals and which can be cost-effectively marketed. The competition has different versions in different regions of the world emphasizing upon the design of Internal Combustion Engine and Electric vehicles. [1]

The AC 15 is most commonly used for the propulsion of formula style, student motorsports car. It is compact, powerful and works efficiently for this type of application. AC-15 is used with continuous power rating of 12kW. It is a 3-phase AC induction motor, by Hi Performance Electric Vehicle Systems (HPEVS). The motor controller used is Curtis 1238E-6501. It is designed for advanced control of AC induction motors and is widely used for on-vehicle traction drive and hydraulic pumps.

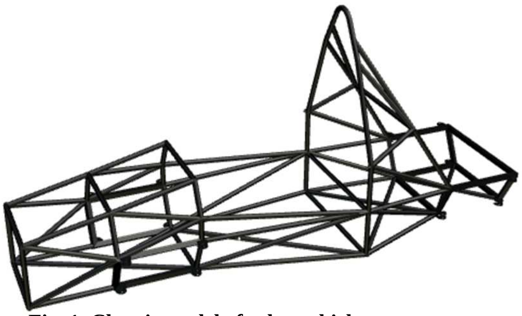
The cells used for the accumulator are Lithium polymer (NMC) pouch cells from EiG Batteries with nominal voltage of 3.65 V and 20 AH cell nominal capacity. Total 120 no. of cells are connected in series-parallel configuration of 20s6p to make nominal voltage of 73V and 120 AH total nominal capacity [2]. The arrangement of cells is packed in accumulator container made up of aluminum having 10 equal sections.

Lithium Pro Battery Management System (BMS) is used for the, over current, over voltage, under voltage and over temperature protection of accumulator. BMS also monitors the State of Heath (SOH) and State of Charge (SOC) of accumulator [3]. Accumulator Isolation Relays (AIRs) are used at each terminal of the accumulator container to protect container poles from exposure to high voltage while the accumulator tractive system is protected by fuse having a current rating less than the maximum switch-off current of the AIRs. The prime protection of tractive system is provided by shutdown circuitry which mainly contains Insulation Monitoring Device (IMD), Master Switches, Inertia Switch, Shutdown Buttons, Brake System Plausibility Device, Brake Over Travel Switch and necessary interlocks.

The performance and cost of manufacturing of the car highly depends upon the material selection and optimized design. The AISI 1010 steel hot rolled tubes are used to get the enough strength for the car which comply the rules for designing the car. Moreover, it can be re-used for other applications as well.

The major challenge associated with the mechanical design of a formula car is chassis which plays a vital role in the structural stability of the car. The other components of the vehicles are directly or indirectly attached with the chassis. The consideration of the safety and comfort of the driver, and accommodation of other components of the car within the space framework is necessary while designing the chassis. The chassis of the car is made of metallic spaceframe by using round tubes of hot rolled AISI 1010 steel. The ease of manufacturing, high tensile strength and low cost of steel associated with the metal spaceframe make us choose it as compared to that of the monocoque chassis.

The triangulation is maintained while designing the chassis for effective load distribution and transmission in order to get stable structure. Moreover, the weight of the chassis is kept low by making appropriate design without compromising the required strength, stiffness and safety parameters of the vehicle. The total weight of the chassis is 44 kg. The metal inert gas (MIG) welding is used for joining the structural members of the chassis. The chassis model of the electric car is shown in Figure 1.

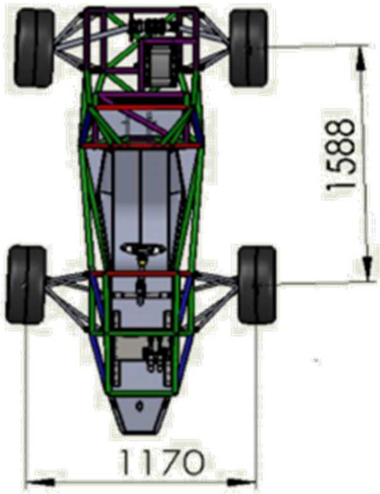


Fig, 1. Chassis model of solar vehicle

The suspension system is designed to isolate the car from bumps and agitation by restricting five degrees of freedom. The optimum design of the suspension system is necessary for grip of the wheels, safety of the car and comfort of the driver. A push rod suspension system is used for all of four wheels in order to provide the wide range of adjustability and packaging option. The short-long arm style of suspension is modified for all four wheels of the car. The standard coil out dampers were used in the suspension system. The stiffness of the springs was 14 kN per meter. The jounce and rebound were 2.54 cm. The major function of the braking system is to stop the car in the minimum distance without affecting the stability of the car. Disk brakes actuated by master cylinder are used in the car. The choice of callipers and rotors is made for the safety and handling of the car.

Track width is measured as the distance between centerlines of right and left wheels and it resists overturning moment caused by the force of inertia at the center of gravity. It also affects lateral force on the wheels of the car. The track width of four-wheeler vehicle is set to be 1.17 meter to accommodate the driver, batteries, motor and, steering, braking and suspension systems of the car. Wheelbase is the distance between the centrelines of front and rear axle which transfers the longitudinal weight. It has a great effect on packaging of components. Therefore, it should be determined at early stages of design. The wheelbase for current design of the car is set to be 1.588 meters.

The direction of the car is controlled by the driver through steering system. The manual rack and pinion steering system is mounted on the base of the frame and is connected with the attachment of the rim through tie rods. The comfort and authority of controlling of driver has been taken into consideration during the selection and designing of steering system. The 79 percent Ackerman geometry of the steering system was decided for effective steering and less chance for slip during cornering. Zero backlash is considered between shaft of pinion and steering wheel. The length of tie rods was 600 mm. the king pin axis was inclined at 10°. The scrub radius was 50 mm. Roll bar was also designed for safety of the driver in case of roll over. The clearance of 4 inches between the head of driver and lower portion of roll bar was maintained. Supporting brackets were also incorporated in design for proper support of roll bar and effective load transfer. Aluminium sheet of 5 mm thickness was used to make the seat. It is light weight and comfortable for driver. The top view of model of the car are shown in Figure 2.



Fig, 2. Top view of model of the car

2. Electrical System Design

The Electrical System of FSAE electric vehicle is divided into two parts, the Grounded Low Voltage System (GLVS) and the Tractive System (TS) [4]. The high voltage system or tractive system contains Motor, Motor Controller, Accumulator, Battery or Accumulator Management System (AMS), AIRs, Main Fuses, High Voltage Disconnect and (HVD) while GLV system is the control system that contains GLV battery and shutdown circuitry including Insulation Monitoring Device (IMD), Tractive System Master Switch (TSMS) and Grounded Low Voltage Master Switch (GLVMS), Inertia Switch, Shutdown Buttons, Brake System Plausibility Device (BSPD), Brake Over Travel Switch (BOTS) and Shutdown System Interlocks. Block diagram of the Tractive System (TS) is given below in Figure 3.

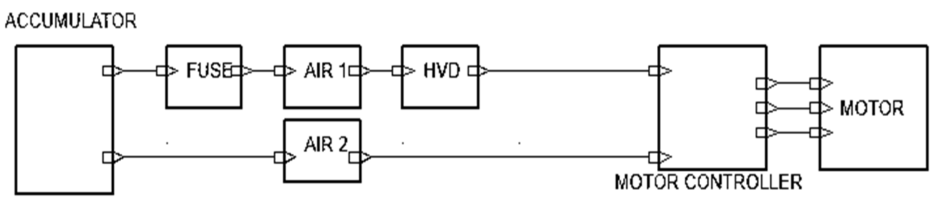


Fig. 3. Block Diagram of the Tractive System

The Block diagram of the Grounded Low Voltage System (GLVS) is given below in Figure 4.

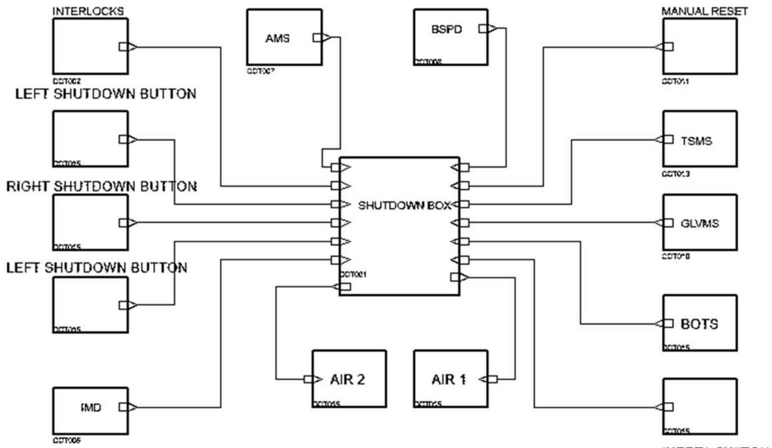


Fig. 4. Block Diagram of the GLV System

2.1. Accumulator

Total one accumulator pack is used which is made up of 120 LiPo (NMC) pouch cells from EiG Batteries. The pack is contained in a single container having 10 equal sections with fire resistant material between them. Each of the 10 cell stacks of 12 cells are configured as 2s6p with nominal voltage of 7.3V and max energy of 3.59MJ and all the 10 stack are connected in series to make nominal voltage of 73V. A high current fuse and two AIRs are used in whole battery pack according to the rules. A distributed BMS is incorporated for the protection of batteries. Current monitoring system is also installed and the load and source (charger) current is monitored by BMS. The main accumulator parameters are given in table 1.

Table 1. Main Accumulator Parameters

Parameters	Value
Nominal Voltage	73VDC
Minimum Voltage	60VDC
Maximum Voltage	80VDC
Maximum Nominal Current	600A
Maximum Output Current	1200A for <10s
Maximum Charging Current	60A
Cell Manufacturer and Type	EiG Battery Li-Po Li[NiMnCo]O2
Cell configuration	20s6p
Total Capacity	31.536 MJ
Total numbers of cells	120
Nominal Cell Capacity	20 Ah
Maximum Cell Voltage	4.00 V
Nominal Cell Voltage	3.65V
Minimum Cell Voltage	3.0V
Maximum Cell Nominal Output Current	5C
Maximum Cell Output Current	10C for <10s
Maximum Cell Charging Current	0.5C
Maximum Cell Temperature (charging)	40°C
Maximum Cell Temperature (discharging)	55°C

The cells used for the accumulator are Lithium polymer (NMC) pouch cells from EiG Batteries (model: C020). Each cell weighs about 482g with specific Energy 174 Wh/Kg and specific power (DOD 50% vvfr, 10sec) 2300W/K. Cells are of automotive grade and rated for 1000 cycle to 80% capacity at 25◦C (DOD 100%). The whole series of these 20s6p cells is protected by a fuse rated at 250A (GSA250). Thus, this fuse protects the conductors carrying the entire pack current of 164A which is motor's nominal current. The electrical configuration of accumulator is shown in Figure 5 and the parallel and series connection of a stack is shown in Figure 6.

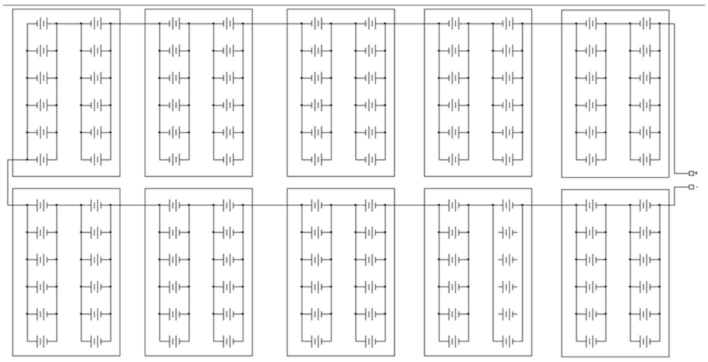


Fig. 5. Electrical Configuration of Accumulator

Fig. 6. Parallel and Series Connection of a Stack

2.2. Battery Management System

Lithiumate Pro BMS by e-lithion is used for under voltage, over voltage, over current over temperature protection. This is a distributed BMS with one master controller and 20 BMS boards monitoring 20 series connected battery packs of 6 cells connected in parallel. The BMS controller is shown in Figure 7:

Fig. 7. BMS Controller

Total 120 cells are divided into 10 banks of configuration 2s6p and the 6 cells connected in parallel are sensed by 1 BMS board, so there are total 2 BMS boards in each stack, one at positive end and other at negative end. The BMS is programmed for upper voltage range, lower voltage range and maximum temperature limit during charging and discharging. On each cell board there is a B- and B+ terminal, and a thermistor is in direct thermal contact with B- terminal to monitor the temperature of each 6p configuration. In this way, all the cells are being monitored by the BMS. The BMS cell board is shown in Figure 8.

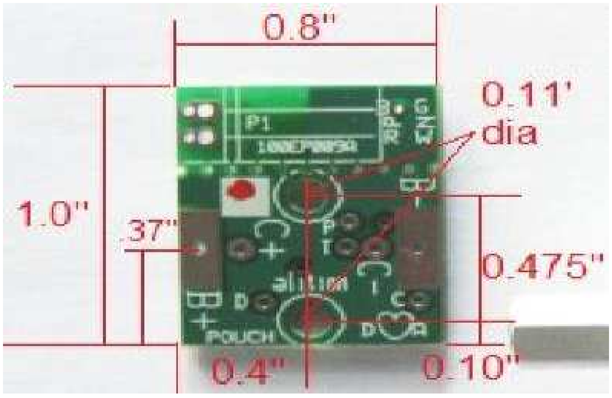


Fig. 8. BMS Controller

The cutoff values of each BMS board monitoring 6p cells are given in table 2.

Table 2. Cutoff Values of BMS Board

Parameter	Value
Upper Voltage Limit	4.0 VDC
Lower Voltage Limit	3.0 VDC
Maximum Temperature while Charging	38°C
Maximum Temperature while Discharging	42°C

The K1, K2 and K3 contacts of BMS reacts in case of any abnormality caused by meeting cutoff values which ultimately shuts down the GLV system using a relay and opens the AIR which cuts the load on the battery.

2.2.1. Depth of Discharge

Power extracted by battery is measured with state of charge. Its value ranges from 0 to 100. When battery is fully charged at no load its depth of charge is zero with increases gradually upon connected external load or Motor. Unit used for depth of discharge is AH and it can be calculated from Eq. (1)

$$DOD = \int (I_{battery} \times dt) \tag{1}$$

Optimum depth of discharge in the design of electric vehicle is set at 70.

2.2.2. State of Charge

Amount of potential gained by battery is calculated with state of charge. It is amount of percentage (%) to which battery is charged. It ranges from 100% to 0%. Initially when battery is fully charged with no load it is 100% which decreases with connected load or Motor. Optimum state of Charge is set at 100%.

2.2.3. State of Health

Battery state of health is the measure of battery efficiency depending upon its internal cell resistance and rated capacity. Increased internal resistance with usage decreases the measure of state of health. BMS extracts the status of cell resistance with capacity of battery to monitor the state of health.

2.2.4. Cell Balancing

Charge stored by each cell of battery depends upon the internal resistance of individual cells. Internal resistance of all individual cells couldn’t be exactly same therefore there is always a slightly mismatch between charge stored by individual cells when connected to common charging source. This mismatch of charge allows discharging the cells at different rate and thus deceasing overall state of health of cells and maximum stored energy. In order to disseminate this power loss BMS performs the operation of cell balancing [5].

All cells are charged up to 0 depth of discharge and maintained at this point during charge depletion process. Charges are added or subtracted from cells to balance complete battery, additional charge is supplied by external charger and surplus charge is released in the form of heat from over charged cells.

2.3. Accumulator Isolation Relays

Two Accumulator Insulation Relays (AIRs) are used, one at each terminal of the accumulator so that if AIRs are open, no High voltage is present outside the accumulator container as required by the Formula SAE rules in order to ensure electrical safety from the container. AIRs are of Normally Open type and driven by the GLV battery. Main Accumulator fuse rated at 250A is protecting the AIRs rated at 400A. The characteristic data of AIRs used is given in table 3.

Table 3. Characteristics of AIR

Parameter	Value
Relay Type	EV200 Series Contactor
Contact Arrangement	SPST-NO
Nominal Coil Voltage	24 VDC
Maximum Operation Voltage	900 VDC
Continuous DC Current Rating	400A
Normal Load Switching	Make and break up to 300A
Maximum Load Switching	10 times at 1500A
Overload DC Current Rating	2000A for 250msec

2.4. Shutdown Circuit

The main purpose of shutdown circuit is to disconnect the power to the tractive system by opening all accumulator isolation relays (AIRs). The shutdown circuitry mainly consist of the following parts.

- Master Switches
- Shutdown Buttons
- Insulation Monitoring Device (IMD)
- Brake System Plausibility Device (BSPD)
- Inertia Switch
- Shutdown System Interlocks

The shutdown circuit joins the different sections of shutdown system into one board. This shutdown circuit carries direct current routed directly through tractive system master switch, inertia switch, shutdown buttons and brake over travel switch and through relays controlled by IMD, BSPD, Arduino (Brake and torque plausibility check) and BMS system and for cockpit and rear reset buttons. The cockpit reset button is a latching button incorporated using relay logic, so whenever the shutdown circuit is open, driver needs to reset the tractive system using this button. If shutdown circuit is opened due to BMS, IMD or BSPD, another latching relay is used as shown in figure below to latch the error so that shutdown circuit does not restore unless this additional reset button is pressed which is inaccessible by the driver. The wire leading to the shutdown circuit from the battery is fused by a 25A as shown in Figure 9.

2.4.1. Master Switches

The master switches are manually triggered switches in the shutdown circuit. There are two master switches in Formula Electric Vehicle which are given below:

- Tractive System Master Switch (TSMS)
- Grounded Low Voltage Master Switch (GLVMS)

TSMS is another switch connected in series in the shutdown circuit path which is responsible to cut the power of shutdown circuit and opens the AIRs.

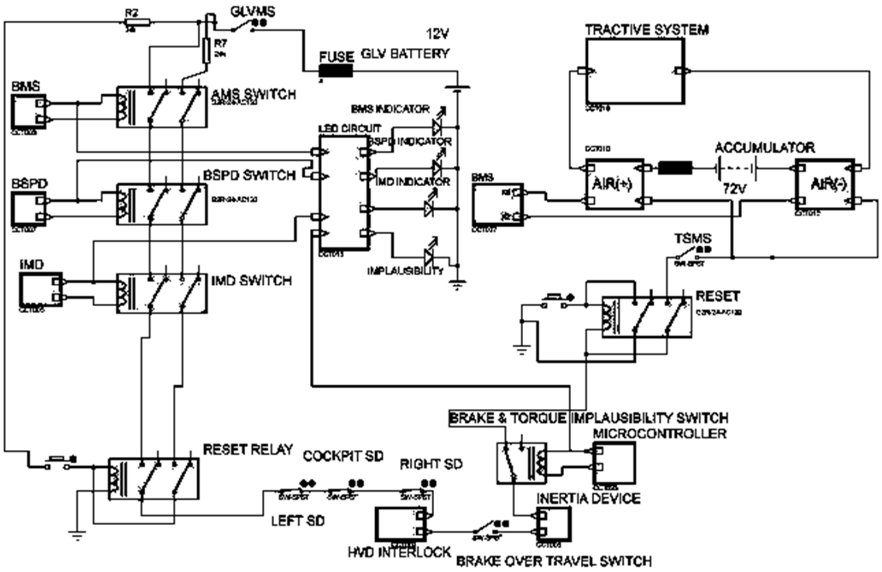


Fig. 9. Shutdown Circuit

GLVMS opens the connection between the GLV battery and GLV system. Since GLV system powers the shutdown circuit and AIRs so cutting the power of GLV system de-energize the shutdown system thus opening the AIRs.

2.4.2. Shutdown Buttons

Three number of rotary shutdown buttons are used in the design on the left side of the car, on the right side and in the cockpit. All the shutdown buttons are directly in series connection with the other components in the shutdown circuit, thus pressing any of these will result in the separation of the accumulators and the tractive system due to the opening of AIRs.

2.4.3. Insulation Monitoring Device

The IMD detects an insulation failure in the wiring of electric vehicle. It will open the AIRs and shuts down the power from accumulator to tractive system if it detects any insulation failure having resistance value less than or equal to 100KΩ in the wiring. The IMD used in the design is the Bender A-Isometer IR155-3203. It is energized by 12V supply. Its output is directly connected to a relay which carries AIRs current, and a small circuit for IMD LED indicator which is placed on dashboard. In normal case when there is no insulation failure IMD output voltage is 5V, relays is closed and LED is OFF and when IMD detects insulation failure its output voltage becomes 0V, relay is open and LED is ON indicating insulation failure. IMD circuit is shown in Figure 10. The parameters of IMD are given in table 4.

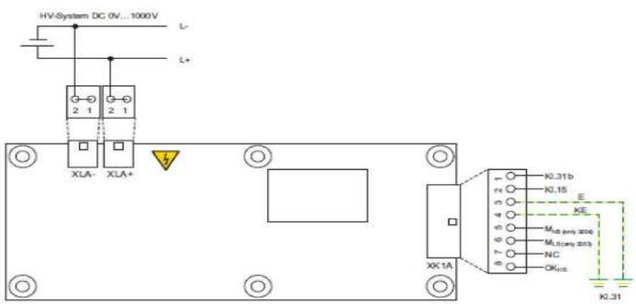


Fig. 10. IMD Circuit

Table 4. Parameters of the IMD

Parameter	Value
Set Response Value	100 KΩ (500Ω/Volt)
Self-Test Interval	Always at start-up, then every 20 minutes
Supply Voltage Range	10-36 VDC
High Voltage Range	DC 0-1000 V
Supply Voltage	12 VDC
Max. Operation Current	150 mA
Approximate time to shut down at 50% of the response value	26 sec
Temperature Range	-40..150°C

2.4.4. Brake System Plausibility Device

The Formula SAE rules requires that the power supplied to the motor must shutdown immediately just after the mechanical brakes are pressed and the same time the signal of the torque encoder is more than 25% pedal travel. In the design of brake plausibility, two sensors are used, one for hard breaking and other one for power measurement. EB100 sensor is mounted on pedal of brake. It gives electrical signal when brakes are applied. This signal is fed to LM339 Comparator for confirmation of hard braking. HTFS 200P/SP2 sensor is used for measurement of current from accumulator to controller. Current sensor signal is also fed to LM339 comparator for confirmation of 69.44A (equivalent to 5 KW). Output of both comparator is fed to AND gate. And Gate output is fed to 8 Bit shift register with clock 15 Hz. An inverted signal of AND gate is also fed to shift register. Output for BSPD is taken from inverted 8th bit. Normally 8th bit is high and BSPD is closed when both signal come from hard braking and torque encoder and persist for 0.5 Sec logic high is shifted from 0th bit to 8th bit and inverted 8th bit becomes low and opens BSPD. If fault is persistent for less than 0.5 sec shift register gets reset. The BSPD circuit is shown on Figure 12.

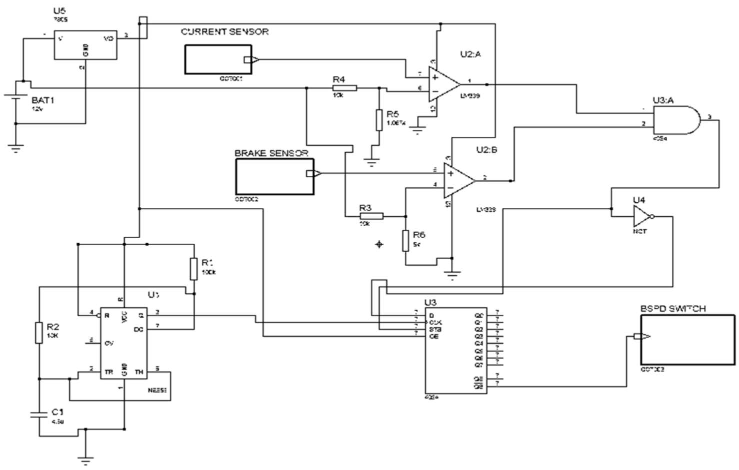


Fig. 12. Brake System Plausibility Device Circuit

2.4.5. Inertia Switch

The inertia switch detects abnormal deceleration. Sensata crash sensor is used as an inertia switch. It directly carries the current of AIRs. The contacts of inertia switch are normally closed. In case of rapid deceleration, contacts open and so the AIRs. The block diagram of inertia switch is given in Figure 11.

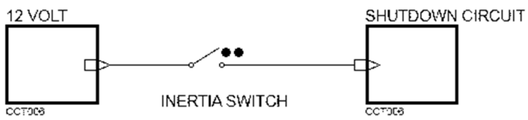


Fig. 11. Block diagram of Inertia Switch

The parameters of Inertia Switch are given in table 5.

Table 5. Parameters of the Inertia Switch

Parameter	Value
Inertia Switch Type	Sensata 360 Resettable Crash Sensor
Supply voltage	12 VDC
Trigger Characteristics	6 g for 50 ms/11 g for 15 ms
Max. Operation Current	150 mA
Temperature Range	-40..150°C

2.4.6. Shutdown System Interlock

The shutdown system interlock is incorporated at High Voltage Disconnect (HVD) Switch in the design. An HVD with integrated internal interlock system is used. Whenever HVD is disconnected, the interlock is opened and the shutdown system gets open, resulting in the opening of AIRs. The shutdown system interlock is shown in Figure 13.

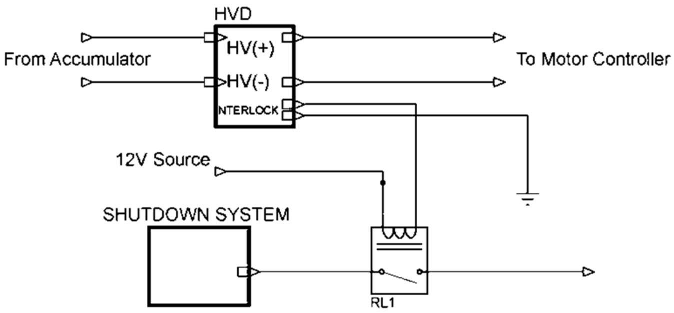


Fig. 13. Shutdown System Interlock

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