Battery Safety System for Electric Racing Vehicle

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Abstract* - The Vermillion racing team is a newly made project on DTU and is working on building an electric race car. The car will be participating the Formula Student Electric competition. More than 100 teams from different universeties will be competing on who can build the best race car. This project is mainly focused on implementing a battery system in the car based on Lithium Polymer technology. When working on batteries, safety is the top priority. The main systems will consist of a BMS to monitor and manage the battery packs. This will be a bought solution, but there is still a lot of research about the batteries required. A power systems board will have to be designed and made. This system will make sure that the battery box will be isolated from the rest of the system in case of a fault or emergency. A seperate system will also be designed and made to indicate the activity status of the battery box. This will have to detect both the outside voltage of the battery pack and the physical state of the relays. This project will be in collaboration with other department spread out on the mechanical and electrical department. All these departments will be under the Vermillion Racing team, and the ultimate goal is to compete and win in the competition.

I. INTRODUCTION

This project is part of a larger project, which goal is to design and build an electric racecar. The car will be entirely designed and build by DTU students and will compete in the Formula Student Electric (FSE) competition at the Silverstone track in England. this project is a part of the Vermillion racing team, which team consist of about 50 DTU students. The Formula Student is a Blue Dot project, and is expected to continue each year from now on. This means that the parts designed and produced in this project will either be optimized or used as inspiration in next years competetion.

This project is focused on the development of a Battery safety system. This system is mainly responsible for monitoring the battery system and disconnecting the battery from the rest of the high voltage system (tractive system) in case a fault is detected in the car. This system will include a Battery Management system (BMS), a Tractive System Active Light (TSAL), and a power systems board.

The battery will be isolated from the rest of the system through a two Accumulator Isolation Relays (AIR). The power systems board will make sure any of the safety systems and shutdown buttons is able to disconnect the relays in case of a fault.

The car will have a large battery container consisting of several lithium-polymer batteries. These kind of batteries contain a large amount of energy that they can discharge very fast. Because of that, it's very important to handle the batteries in the right way to make sure the car and the people close to it are safe.

Working with the batteries is not easy, and a lot of safety precautions have to be made. It's important to know exactly which state the batteries are in. If the batteries are not in use, or if an emergency should arise, it's also important to be able to disconnect the battery box from the rest of the system.

There are three main problems which arise when working on a battery system:

1. How can we monitor and manage the battery within safe conditions?
2. How can we make sure that the battery is only connected to the tractive system when it's safe and desired?
3. How can we indicate the activity status of the tractive system?

II. "PROBLEMS AND RISKS"

Lithium Polymer (LiPo) batteries have a large advantage over other battery technologies as they have a high energy density and discharge rate. This makes it possible for the car to drive further and accelerate faster. The disadvantage is that they are more complicated to operate, and they are more dangerous if a fault should occur.

Different problems can arise when working with LiPo batteries. The battery packs consist of smaller cells, and if their voltage is too low or high, or if the voltages of the cells are not balanced, the battery can destroy itself and in the worst case ignite or explode. This kind of battery have a very high discharge rate and high capacity, if a load draws too much power or if the battery is shorted, it can overheat and ignite or explode. The battery in the car is made out of several smaller packs packed into a box. If the battery box is not operated safely, there is a risk of fire, explosion and/or electrocution. The safety of the battery system is therefore the top priority for this project.

The battery packs will be mounted in a large battery box. To monitor and regulate the battery box, a BMS must be implemented in it. The BMS will constantly measure the voltage of all the cells and make sure they are at a safe level. The total power output of the battery box will also have to be measured to make sure that the connected load won't draw more current than the batteries can safely provide. Several temperature sensors will be mounted inside the battery box to make sure the batteries are not overheating. To charge the battery, a charger made for the battery setup is necessary. The charger will communicate with the BMS over a CAN bus so the cells can be balanced correctly and so the battery won't get overcharged.

The battery box will be connected to a pair of motor controllers which controls the motors and decides how much power is used by each motor. These motor controllers have a high capacitance. Because of the high discharge rate of the batteries, a pre-charge system must be implemented to limit the in-rush current to the motor controllers. Otherwise, the relays may weld shut and it wont be possible to open them again. The pre-charge system will charge the motor controllers capacitor banks via a power resistor to limit the current. When the outside system voltage reach at least 90% of the full battery voltage, it is safe to close the main relays.

When the battery box is disconnected again after use, the capacitor bank in the motor controllers will still be charged. Therefore, a discharge system will have to be made. The discharge system will dissipate the remaining energy in the motor controllers through an array of power resistors. This should happen in less than 5 seconds to make sure the car is safe after the battery box has been disconnected.

Beside potential battery faults, many other faults and dangers can occur in a race car. These faults can be either electrical errors or accidents. If these faults occur, it can be dangerous to the driver and it can destroy the electrical system. It is therefore important that the battery box is quickly disconnected from the tractive system if a fault or accident should happen.

Some of the faults that can occur are isolation errors, battery errors, crashing and brake errors. The isolation error can be detected by using a device which can measure the low voltage system and the battery box and trigger if an isolation error has occured. We need to make sure that the battery box will be disconnected from the tractive system in case the car is in a crash to limit the risk of short circuits and electrocution. To ensure the car is used correctly, the car should only start when the driver and the team is ready to drive the car. It will therefore be needed to have a master switch which will be used to turn on the tractive system. To make it possible to work on the low voltage system without having to remove the low voltage batteries, a master switch to connect the low voltage battery to the low voltage system is needed. Several emergency shutdown buttons will also be mounted on the inside and outside of the car to make sure any person can disconnect the battery in case of an accident. Because the electrical system will be used in a car, there is a risk of water damage and the car shaking. To protect the electrical components in the car, all components must either be water proof or placed in a water proof container. They will also be mounted securely to the car so they wont shake out of place

To indicate that the battery box is completely disabled and all the relays are open, a Tractive System Active Light (TSAL) must be implemented. The TSAL itself can't affect the electrical system, and is only an indication of the battery box status. Even though the battery box have several safety systems, it's important to have a seperate system to monitor and indicate the activity status of it. This ensures that a person can see clearly if the car and battery box itself is safe to be around. Because the TSAL is isolated from the rest of the system, a fault is unlikely to affect the function of the indicator.

To ensure that the TSAL always indicate the status of the battery box, it will have to measure the physical state of the main relays (AIRs) and the outside system voltage present on the battery box terminals. It will be measured by non-programmable logic which is only powered by the battery. If any of the relays are physically closed or if the outside system voltage exceed 50 V, the TSAL must blink red. If all relays are open and the outside voltage is below 50 V, the TSAL will switch to a constant green ligth.

III. "RESEARCH AND DEVELOPMENT"

The problems and risk mentioned in last section have to be solved so that the car is both safe for use but also compliant with the FSE rules. This means that our solution will be heavely influenced by the rules so that the car can compete in the competetion without any penalty points.

All the faults described in the previous section are used to decide when the car is safe to drive. All these faults will be detected by seperate systems in the car, and when these faults are detected, the AIRs will open and isolate the battery. To make sure that the AIR's are only activated when desired, the current activating the AIR's must be directly supplied by the low voltage system and flow directy through the relays, switches and buttons that activate them. This is done so each part of the safety system can directly stop the current from reaching the AIR's. The safety system will be centered around a power systems board. This board will be a PCB and is where the relays will be placed. These relays will then be closed by their respective safety systems. All these relays, buttons and switches are a part of the low voltage system and use 24V. The power systems board will also have the relays necessary to control the pre-charge and discharge phase along with relays to control the individual AIRs. This is mainly used by the BMS. As the pre-charge and discharge systems are connected directly to the tractive system, they are galvanically isolated from the low voltage system present on the power systems board.

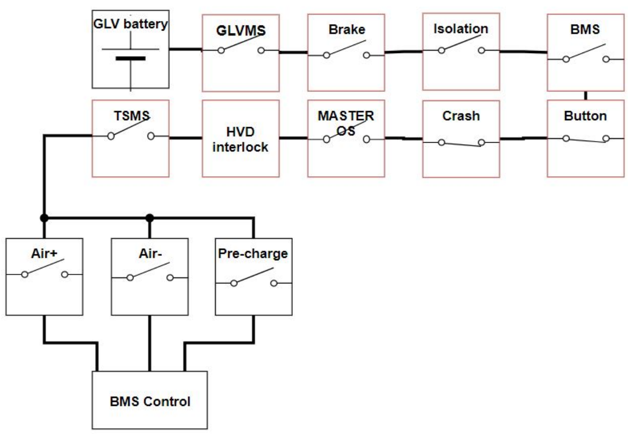

Fig. 1. Simple block diagram of safety system

Figure 1 shows a blockdiagram of the safety system responsible for opening and controlling the AIR's. The first block after the low voltage battery is the Ground Low Voltage Master Switch (GLVMS). This switch supplies power to all the systems in the car which use 24V, and is the first swich needed to be turned on in order to start the car. This is a master switch, and it is important that it will not be turned when it is not needed. When the switch is turned off, the handle can be removed and the switch can be locked and tagged.

The brake errors consists of two subsystems. The break system plausibility device make sure that the battery is disconnected if the car is accelerating and braking at the same time. This means that the driver can always stop the car if the accelerator is stuck due to either software or hardware fault. The break overtravel switch will disconnect the battery if the break pedal is pushed all the way down. This can happen if the brake fluid is leaking. These are not systems designed in this project, but they will have a relay each on the power systems board.

The isolation error is detected by a *BENDER ISOMETER® IR155-3203/IR155-3204*. This part is required to be used by the competetion, and makes sure that the battery is always isolated from the low voltage system and the car chassis ground. The relay will have to be latched so the battery is disconnected until the fault is inspected and fixed.

The BMS relay in the safety system is latched in the same way that the iosolation is. Both the Isolation and the BMS need an indicator light on the dashboard of the car, so the driver and the team know where the fault lies. This light needs to be on until the relay on the power systems board has been manually reset. These indicators will be controlled directly by the cars master controller.

Three emergency shutdown buttons will be located on the car. One in the cockpit and one on each side of the car. According to the rules of FSE, these buttons must either be push-pull or push-rotate, and all three buttons must be able to disconnect the current flow to the AIR's directly.

The crash sensor is a 360 degrees sensor which detects impact load. When an impact load between 6g and 11g is detected, it opens the safety system. The crash sensor can be reset by pushing a button on the device.

The master controller will also have a relay on the power systems board, and in therefore able to connect and disconnect the battery when starting and stopping the car. It is therefore also able to disconnect the battery in case of a fault.

The next box in figure 1 is the High Voltage Disconnect. It works by opening the safety system when the cable connecting the battery box and the motor controller is disconnected. This is done through a interlock.

The Tractive System Master Switch (TSMS) is the last link in the chain. This is a physical switch identical to the low voltage master switch, and is used to turn on the tractive system.

The tractive system can be activated when none of the parts of the safety system have detected a fault, all of the switches and buttons are closed and the driver has entered the ready to drive mode using the master controller. The relays controlled by the BMS are used to control the pre-charge sequence. After a engine start is requested, the master controller will request the BMS to run the pre-charge operation.

The discharge relay is controlled by the same signal going from the tractive system master switch to the AIR's. The relay is normally closed, which means that the discharge phase will run automatically when the battery is disconnected.

All signals which control whether the AIR's are opened og closed are system critical. This means that they must be protected agains short circuit and open circuit. If a signal wire is broken, the relay it's connected to will automatically open. If a short circuit of the signal wire is present, a fuse will blow and the relay will open. Therefore, all signals will go to a safe state if there is open circuit or short circuit.

In the beginning of the project, the battery setup was already set to a voltage between 80-120 V. The BMS was chosen to be a *LiBAL N-BMS* as *Lithium Balance* would like to sponsor it. The system is very flexible and can work with several battery configurations. Because of that, most of the work was already done with the BMS.

In 2, a simple block diagram of the battery system can be seen. The BMS consist of a master board with three slave boards connected to it. The battery systems is made of 7 battery segments in series each consisting of 6 battery packs in parallel. Each segment will have 4 temperature sensors and 4 cells which voltages are monitored by a slave module. The slave boards are able to measure the voltage of the cells and balance them through on-board resistors. The battery temperature can also be measured in several different locations using external sensors. The master board is measuring the total battery voltage along with the cell voltages and controlling the charging and balancing of the cells. Through a hall-effect current sensor, the current through the battery is measured to ensure the safety threshold is not exceeded. Using three external relays located on the power systems board, the BMS master is able to close the two AIR's and the pre-charge relay to control the pre-charge operation safely.

The rules specified that a third of the cells must have a temperature sensor mounted at the negative pole. This was problematic for both the BMS and the battery box itself. All the temperature sensors would cause space problems in the pack because of the cables, and the BMS would not be able to monitor all the sensors without getting extra slaves for it. In collaboration with our advisor, Nenad Mijatovic, and the battery group, Albert Segilmann and Frederik Højlund, a solution was found where one sensor could measure the temperature of two cells. This made it possible to fit the whole battery system in a small closed container.

The TSAL was complicated to make because of the high safety factor and many rules. It was not allowed to measure the control signals to the main signals, and must do it by directly measuring on the relay terminals. This was to make sure the TSAL measures the right state in the event that the relays got stuck or welded shut. It was also necessary to power the TSAL with the high voltage battery and not the smaller external low voltage battery. This was to make sure the TSAL would always be powered on when the battery was connected. In 3, a simple block diagram of the TSAL can be seen.

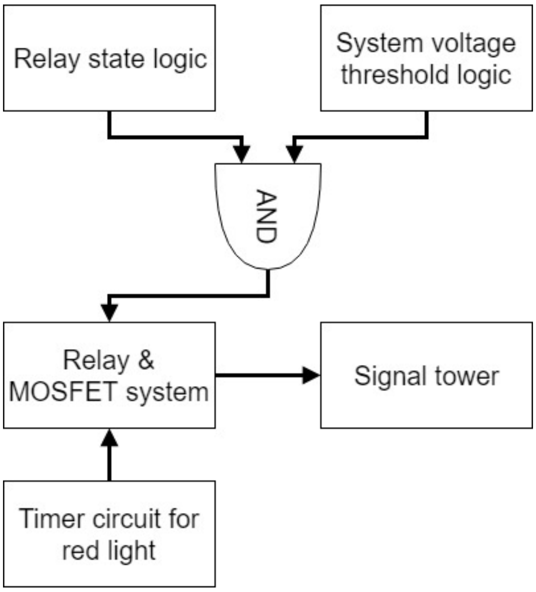

Fig. 3. Simple block diagram of Tractive System Active Light (TSAL)

To make sure the system will not indicate a safe state if an unknown input occur or if the trigger circuit breaks, the default state of the circuit is set to indicate an active battery. This is done via switch relays which will have the normal position blink the red light. Two independent circuits will have to both indicate a safe state, represented as the AND-gate, for the light to switch green and indicate a deactivated battery. In reality, two transistors and a relay will be in series acting like an AND-gate.

The *Relay state logic* will determine the state of the two main relays through a resistor. The output of the resistor network will be compared to a reference signal via two op-amps. The measured signal and reference signal is both referenced to the supply voltage, thus making it possible to work with the large range of supply voltages which occur depending on the battery charge level. Each op-amp will trigger a transistor, and if both op-amps are triggered, both relays will be open and indicate a safe state.

The *system voltage threshold logic* will independently measure the voltage over the battery terminals on the outside of the battery box. If the threshold of 50V is reached, an op-amp will open a relay and indicate an unsafe state. If the circuit is below 50V or completely unpowered, which will be the case if one or both of the relays are closed, the relay will close again and indicate a safe state.

If both circuits indicate a safe state, the light will switch to a constant green via switch relays. If that is not the case, the circuit will blink the red light via the timer circuit. If the circuit lose a connection to the batteries, it would not be able to determine the relay state and battery voltage. But because it's powered by the battery, the TSAL will be unlit, and therefore indicate an error and potential unsafe state.

IV. PRODUCTION AND TESTING

The power systems board will be a PCB. This PCB mainly consists of relays and connecotors to the varius parts of the safety system. The power systems board will have both low voltage and high voltage systems. These needs to be proberly isolated from each other, which is done by placing each system at least 20 mm from each other on the PCB. The low voltage and high voltage is placed on the same PCB to save space and make a more simple system. When the power systems board has been completed, it will be placed in a closed box with waterproof connectors.

To make sure that the power systems board works properly, the board needs to be tested. The first test is to make sure all the relays and buttons work as designed. The buttons and switches will be directly connected to the power systems board, and the signals from the active systems will be emulated with a power supply.

A Arduino will be connected to an array of relays. These relays will be connected to a variable power supply to emulate different signal voltages. The Arduino can be programmed to test the relays on the board in different state configurations. By changing the voltage on the power supply, a large range of signal voltages can be tested to make sure that the system can will still work over a larger range of input signals. This is good to know in case some of the systems can't supply a steady signal voltage.

It is important to test all possible connections on the board with a multimeter while activating the relays. This is done to test if the board is printed and designed proberly. If this test is succesfull, it would confirm that the design of the power systems board works correctly. This test will be done using the equipment in X-lap.

The second test is a test to make sure the pre-charge and the discharge relays works properly. This will be done by connecting a capacitor to emulate the motor controller. A power supply will be connected to emulate the battery box. During the test, the temperature of the resistors will be monitored to make sure they aren't overheating.

Before mounting the batteries in the container, the BMS and all battery-related systems must be tested and approved. The test setup will be close to the one illustrated in 2, but with a few modifications. The first tests will consist of one master and two battery packs, keeping the voltage at a minimum while still being able to configure and test the BMS functionality. If the test is successful, more batteries can be added in series until the full system voltage is reached using all three slaves. The load will be in the form of an adjustable load able to dissipate all the heat, but it will only be connected after the BMS is fully configured and working. This should be connected in combination of the main relays and power systems board to test if they can safely disconnect the battery. If anything unexpected should occur under testing, this will also be used to isolate the batteries and prevent an accident.

The charger we're using will also be testet, where it's important to check if the CAN communication between BMS and charger is working. The BMS is also checked to see if the cells are balanced and charged to the correct voltage. If there is time en resources available, it will also be possible to tweak the PID parameters of the charging operation to keep the charging time to a minimum. But this will have to be monitored closely as a underdamped PID regulation could overcharge the batteries.

It's important to also test the batteries in combination with the rest of the system. The relays and power systems board should be tested first, but the TSAL can also be tested easily when all the batteries in series is connected together to reach the full system voltage. Afterwards, the system will have to be implemented in the battery box where temperature tests are especially important. If the cooling in the box isn't suffucient, the batteries can overheat in the closed container and ignite.

The TSAL will be made out of simple electronic components and soldered onto a PCB. The PCB will be fit in a waterproof box which is easy to install on the car later on. In the testing phase, a milled prototype PCB will be used. This is cheap to make and fast to mill if a correction have to be made.

To test the *relay state logic*, a 30V power supply is enough to power the logic and the light. A small relay will be used to emulate the function of the main relays. The four possible states of the two relays is tested, where it is expected for the light to stay red until both relays are open.

To test the *system voltage threshold logic*, a supply of 60V is required. While the two relays are open, the supply is increased until around 50V where the light is expected to trigger. This will also be tested with the other possible relay state combinations to make sure that the two circuits work together.

If both tests are successful, the circuit will have to be tested at the full 120 V to make sure the regulators work at higher voltages without overheating. At last, the TSAL will be tested with the full battery setup including the two main relays and the pre-charge relay. Afterwards, the TSAL can be implemented in the car.

V. CONCLUSION

Through this project, we have learned a lot about how to design and build a safe electrical battery system for a car. We have focused on what to do to protect and regulate the battery, and when to disconnect the battery from the rest of the cars electrical system.

A BMS system have been designed to monitor and regulate the batteries. The system have not been implemented yet due to delay in the BMS delivery, but the battery setup have been designed along with the tests required to make sure the BMS is working as expected.

A power systems board have been designed and the first prototype is close to be ready for testing. It is expected to go into testing shortly after the project is done. Based on the test, the design will be improved and in the end send to production at a professional PCB manufacturer.

The first design of the Tractive System Active Light have been tested, where it successfully measured when the outside system voltage reached a threshold of 50 V. The part of the circuit to check the physical state of the main relays did not pass the test, but a new design have been made and a new prototype is close to being made. This circuit will also be manufactured by a professional PCB manufacturer when it is fully tested and approved.

Overall, we are pleased with the progress we made throughout the project. we unfortunately didn't implement all the systems, but we learned a lot about working on larger projects and collaborating with other departments.

ACKNOWLEDGEMENT

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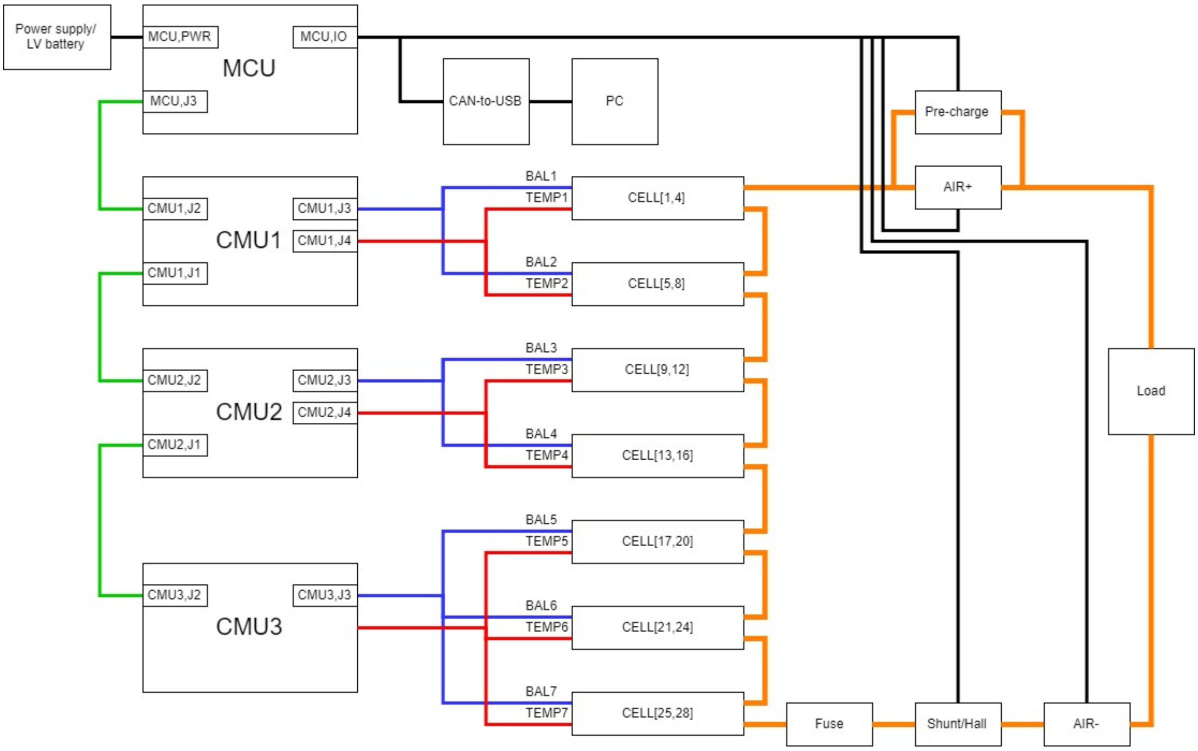

Fig. 2. Diagram of the battery system