Design and Implementation of a Drivetrain for an FSAE Electric Vehicle

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***Abstract*—This paper describes the design and implementation of a drivetrain for a Formula Society of Automotive Engineers (FASE) electric vehicle. The specifications used to design the system were provided by SAE in the Formula Hybrid SAE rules. The custom designed central Tractive System Control Board (TSCB) communicates with Supervisory Control and Data Acquisition (SCADA) system, motor controller, Accumulator Isolation Relay (AIR), and the Battery Management System (BMS) of the vehicle. A detail description of the TSCB and its integration with the vehicle systems as well as test-drive results are presented.**

Keywords—electric vehicle, drivetrain, tractive control, fault detections

I. Introduction

Electric car industry has been expanding rapidly for the last one decade despite many challenges. Only 55 thousands plug-in electric vehicle was sold in the United States in 2012 compare to more than 400 thousands in 2018 [1]. More and more vehicle manufacturers has been investing in electric vehicles due to their technical and environmental benefits. Engineers with experiences in electric vehicle design, build, and test are key to the future environment and economy. Engineering seniors at York College of Pennsylvania took on a challenge to build an FSAE electric vehicle from the ground up. 11 students (5 mechanical engineers, 3 electrical engineers, and 3 computer engineers) were involved in this capstone project. The electric vehicle team was divided into four sub-teams: mechanical design, drivetrain, energy management, and supervisory control and data acquisition. The drivetrain team was responsible to design and build a high power circuit for the electric motor and motor controller that meets FSAE safety requirements. Design and build a low power circuit for the battery and motor controller cooling system that meets FSAE specifications [2]. Configure and interface the motor controller with the electric motor. This paper describes the detail design work as well as the integration of the drivetrain with the vehicle systems.

II. Drivetrain

Electric vehicle drivetrain consists of three main parts: an electric motor, a power electronic converter, and a controller unit. There are few options for motor such as dc motors, brushless dc motors, induction motors, switched reluctant motors, permanent magnet synchronous motors, etc. For automotive applications power to weight ratio is very important and shaft torque at peak speed are crucial. After considering all available options EMRAX208 (permanent magnet synchronous motor) was selected for its 10 kW/kg power to weight ratio, up to 80 Nm of continuous shaft torque, peak power of 75 kW at 6000 RPM [3]. A Unitek Bamocar D3-RS motor controller is selected as the power electronic converter for its versatile adaptability. This converter together with a motor forms a four quadrant drive unit with driving and braking with energy recuperation in both directions [4]. The other essential component of the drivetrain are a Battery Management System (BMS), Accumulator Isolation Relays (AIR), high voltage bus, Grounded Low Voltage (GLV) system, and a mechanical system to transmit the torque from the motor shaft to the wheel. At the heart of this drivetrain is the custom designed control board, TSCB. This control board communicates with all peripheral sub-systems to maintain safe and secure operation. A system level functional diagram is shown in Fig. 1. The following sections briefly describe each sub-system of the drivetrain except TSCB.

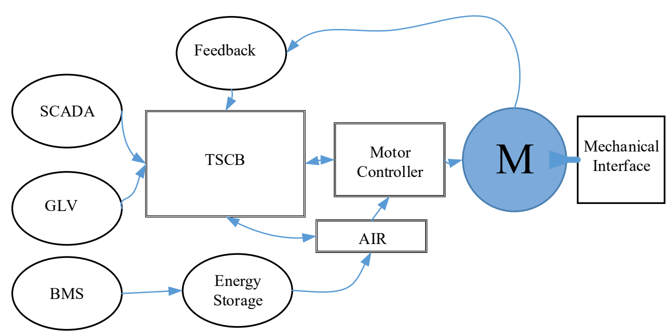

Fig. 1: Functional diagram of the drivetrain

A. Accumulatro Isolation Relays (AIR) and Pre-Charging

AIR controls the high voltage flow in the drivetrain. Three relays are used to control the high voltage connections at the negative terminal, a resistive path to the positive terminal, and a non-resistive path to the positive terminal. A pre-charge circuit accomplished the task of applying high voltage to the motor controller by decreasing the in-rush current. This circuit was designed based off of specifications by Unitek [4].

B. SCADA

The main goals of the SCADA system are the processing of multiple input sources and distributing that information to applicable systems pertaining to control of the motor, battery management and static data storage. An Electric Vehicle Operating System (EVOS) was developed as a part of the SCADA system to maintain a reliable operation. The EVOS is broken into “Stages” being: boot test, standby, pre-charge, energized, driving, and shutdown. This ensures that code won’t be executed out of order, such as if the driver presses the ready-to-drive (RTD) button in standby mode where they have not been progressed through pre-charge and energized stages. StageManager.cpp is the core of where all this stage management occurs.

C. Grounded Low Voltage

The grounded low voltage (GLV) powers main brain, pump unit, and all other accessories such as dashboard indicators, BMS logic circuits, and brake lights. The GLV goes through fuses, shutdown switches, and GLV master switch to maintain a safe operation.

D. Motor Controller

The motor controller interacts with the main brain via a controller area network (CAN) bus. The main communication lines are the pre-charge done check, setting the RPM set-point, and checking for errors and warnings. The pre-charge done check is accomplished by giving the motor a specific amount of time to charge once the pre-charge stage is started. Then the main brain checks to ensure the charge on the motor controller is within about 75% of the expected charge based off the total battery voltage. The RPM set-point is accomplished by measuring the percentage of the pedal press and translating that percentage to a motor controller resolution value that would be equivalent to the same percentage. That value would then be sent by the main brain to the motor controller by the CAN bus. The checking of the motor controller error and warnings is accomplished by the main brain by checking the value of the error/warning register via the CAN bus.

E. Battery Management System

The accumulator uses two packs of thirty six lithium-ion cells in series. Each pack has 5.98 MJ of energy, just under the regulation requirements. The BMS interacts with quite a few subsystems, more importantly with the accumulator, SCADA, and the safety system. The BMS needs to extract information from the Accumulator through voltage taps and thermistor taps contained in the Accumulator Segment design. SCADA receives information through the CAN bus and with various analog and digital IO as needed. The BMS is able to independently trigger the safety circuit to shutdown of the whole car in case of emergency. A 96-cell Orin BMS is implemented to achieve these functionalities [5].

F. Mechanical Interface

The mechanical drivetrain consists of a motor shaft driving a sprocket where a chain connects the driving sprocket to the driven sprocket. The driven sprocket is connected to the differential by a flange. Tripod bearings are placed on both ends of the drive shafts where they meet tripod housings at the differential and the spindle on either side. The spindle fits into the rear uprights with a bearing and is connected to the hub by bolts. The hub is bolted to the rear wheel where power is sent to the ground.

III. Tractive System Control Board

Combinational logic circuit has been used widely to control drivetrain operation due to its ability to detect failures to assure a safe operation [6, 7]. Combination-logic circuit is based on threshold values and is free from extensive data analysis and processing such as fast Fourier transform (FFT) neural networks, and fuzzy logic based fault detection circuits [8, 9, 10, 11]. Tractive system control board (TSCB) is designed to achieve the following functions: 1) diagnose faults at multiple drive component accurately with a single simple method; 2) a simple straightforward implementation; and 3) a system-level supervision. The control unit uses existing sensors and command information to make decisions. This unit has the capability of diagnosing faults during the dynamic and steady-state operations. The TSCB consists of the following sub-systems:

A. Timing Circuit

The TSCB contains two identical timing circuits that are used for different functions. Both timing circuits use a comparator and an S-R latch to make decision. Timing circuit 1 monitors pre-charge operation to control the resistive path AIR. The pre-charge circuit accomplished the task of applying high voltage to the motor controller by decreasing the in-rush current. This circuit was designed based off of specifications by Unitek, the company that makes the motor controller. Once the pre-charge is completed, timing circuit 1 sends a signal to open the resistive path AIR. The timer circuit needs to make sure that non-resistive path AIR is closed before the resistive path AIR is disengaged. It is important to have the non-resistive path AIR engaged during the normal operation to avoid multiple AIR operations during an emergency situation. Additionally, if the resistive path AIR remained engaged then the TSCB would draw more current from the GLV batteries.

The second timing circuit controls when the “RUN” signal for the motor controller goes high. The SCADA system enables the “SCADA_DRIVE” signal which in a broad overview enables “RUN” signal for the motor controller. This “RUN” signal is the last step in enabling the motor controller, it effectively puts the motor into drive mode. The timer ensures that the “RUN” signal is enabled at least 0.5 seconds after the ready for enable (RFE) has been enabled. This is a requirement from the motor manufacturer Unitek.

B. Logic circuit

The Formula Hybrid SAE rules require that the high voltage system can only be controlled by a non-programmable logic in order to increase the safety of the system. This combinational-logic circuit fully complies with the rules and engages and disengages the high voltage system as well as controls the motor controller inputs based on the sensory and command information.

The logic circuit monitor signals from the shutdown circuit, SCADA, and motor controller. If there is a fault in the safety circuit, the shutdown system will send a high signal to the logic circuit. In this situation the high voltage system will be disengaged and motor controller will be notified within 100 ms prior to losing the dc high voltage connection by disengaging the "RUN" and "RFE" signals to the motor controller. An appropriate RC circuit is deployed to maintain the time delay.

The SCADA sends the "SCADA_NOM" digital signal to the TSCB digital circuit to update the status of GLV and battery systems. When this signal is high, it indicates that the GLV system is operating normally, the high voltage battery is not below 20%, the GLV battery is not below 20%, and no errors are present in any systems. If this signal goes low, a shutdown procedure initiates.

The motor controller sends a digital signal to the TSCB logic circuit to notify that pre-charge has been completed and to engage the non-resistive AIR to the motor controller and disengage the resistive path AIR at least 0.5 seconds later. SCADA_DRIVE signal from the SCADA system put the vehicle into drive mode and keep it in drive. This section of the logic circuit combines this signal with the motor controller digital signal to achieve the goal of keep the car running even if the charge falls below 90%. Fig. 2 shows the printed circuit board (PCB) of the TSCB module. The PCB board has appropriate connections for SCADA, motor controller, AIRS, and BMS system.

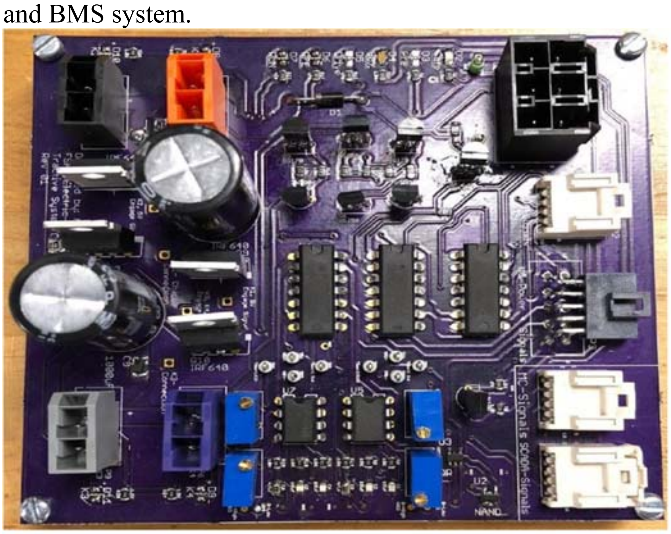

Fig. 2: Physical PCB of the TSCB

C. *TSCB operation*

SCADA Nominal signal notifies the TSCB once the GLV system is up and operational. If this signal is ever low then the high voltage system will shut down. This is used to verify that GLV is operating nominally but also when the high voltage system needs to power down for GLV to shut down or go into standby. The SCADA pre-charge signal initiates pre-charge by closing the appropriate AIRs. Once the pre-charge complete signal has been received from the motor controller to the TSCB, the RFE is enabled, engage the non-resistive path on the AIRs, disengage the resistive path on the AIRs, and the signal is also sent back to SCADA for the notification that 90% charge has been completed. Once the driver is ready to put the car into drive, a button on the dash called "Ready To Drive" (RTD) is pushed and the SCADA sends the SCADA_Drive signal to the TSCB. Once the SCADA_Drive signal is received from SCADA, the TSCB enables the RUN signal for the motor controller. Once the RUN signal is received by the motor controller, the motor controller is ready to accept speed command values from the SCADA via CAN bus.

The SCADA system handles the processes for setting the designated RPM of the motor, monitoring the error and warning register of the controller, determining when pre-charging has ended and logging any useful information for the motor controller. The last main connection that goes to the motor controller is the resolver. The resolver is feedback loop from the motor to the motor controller. It translates motor information such as RPM, temperature, and position to the motor controller. Those values can then be monitored via the CAN bus. The motor controller also has interior settings that determine how the motor controller reacts to RPM inputs.

IV. System Integration

The tractive system control board (TSCB) is the most crucial component of the drivetrain because it enables high voltage and provides inputs to the motor controller and disengages them as well in all circumstances. The TSCB is mounted in the low voltage section of the battery box along with shutdown circuit and resolver. The component in this box communicate with SCADA, motor controller (MC) and high power circuit and GLV as shown in Fig. 3.

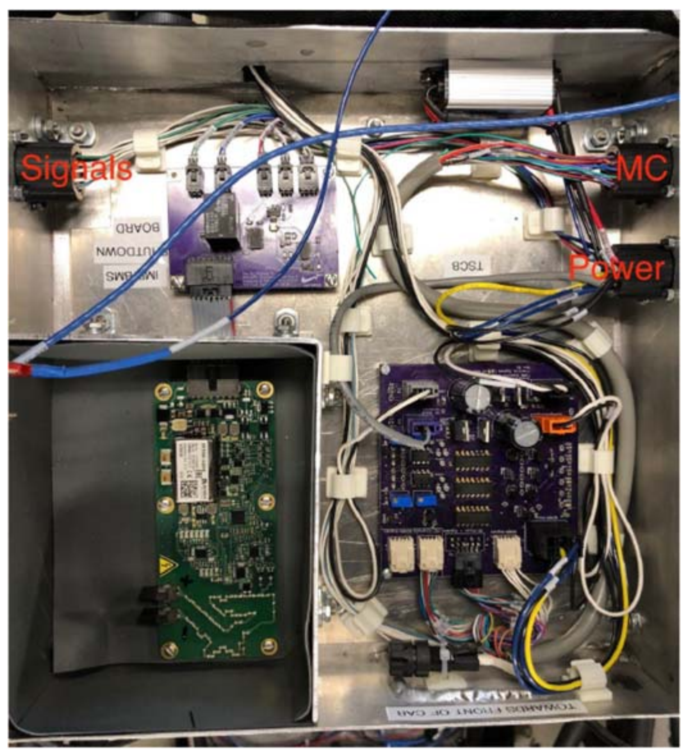

Fig. 3: The TSCB board along with shutdown circuit and resolver

The AIRs and pre-charge circuit are placed into its own box that is part of the battery box. The discharge circuit is mounted in its own box along with the TSAL. It was mounted just below the motor control and its connection included the connection to the positive and negative dc connections of the motor controller. Fig. 4 shows the complete the vehicle with the design team.

Fig. 4: The vehicle with the design team

V. Field Test

After the successful integration of the drivetrain with all other sub-systems of the vehicle, a series of tests were conducted in the laboratory to make sure that the vehicle was functioning as expected. During the few issues were noticed by the design team.

A. Chattering AIRs

The AIRs were not engaging correctly. The relays would constantly open and close repeatedly for few seconds. To fix this the TSCB was modified in three locations to add diodes and resistors. Diodes allow a current limiting resistor on charging of the capacitor but not on discharging of the capacitor.

B. Discharge timing circuit capacitor

The TSCB was modified to include a 100 kΩ resistor to each timing circuit to discharge the capacitor within 0.5 seconds of losing the signal so that the timer could be used relatively sooner if the car went to standby and then pre-charged moments later. Before the modification either TSCB signal needed to be cycled to start backup immediately or it needed at least 3 minutes to slowly discharge below the threshold.

C. Shutdown circuit transistor

The final modification to the TSCB was needed to prevent a transistor from burning up. The shutdown circuit converts a 24 V signal to 5 V signal using a transistor and resistor. This transistor was supplied with a 24 V at the gate, which was causing the problem. The gate signal was decreased to 5 V using a resistive circuit at the gate to stop the burning up.

After the intensive and comprehensive testing in the laboratory, the design team took the vehicle for a test drive. Appropriate safety precautions were in place during test drive. The vehicle completed several rounds in a parking while team members took their turns. The vehicle accelerated to 25 km/h without any problem.

VI. Conclusions

A drivetrain control system based on combinational is designed and implemented for a Formula SAE electric vehicle. This tractive system control board (TSCB) works with other subsystems such as SCADA, motor controller, motor, BMS, GLV, and shutdown circuit to maintain a safe operation of the vehicle. The TSCB was validated by extensive laboratory tests and test drives.

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