SiCverter

(Silicon Carbide Inverter)

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ECE 445 Project Proposal – Fall 2020

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1 Introduction

1.1 Objective

The problem is that all commercially available drive inverters capable of driving 35kW motors at 600V are too expensive and/or too heavy to be useful in our race car.

Our solution involves a design that will use high efficiency silicon carbide MOSFETs, high energy density film capacitors and a high-performance microcontroller from TI designed to function well in motor drive applications. It will be designed as a standard voltage source inverter with 3 phase legs and current sensing for all 3 legs for redundancy and noise immunity. A Field-Oriented Control Algorithm will be used to modulate the phase currents and maximize motor efficiency and performance. A motor resolver using a BiSS interface along with a dual CAN communication network will be used for noise immune communications on the vehicle. Four of these inverters will be placed on a single large heatsink instead of the industry standard method of using a complex liquid-cooled cold plate. However, this will require ~99% efficiency from the inverter which we believe to be possible. Once achieved, we will have created a lightweight solution with very high efficiency that will cost much less and have more than double the power density of the best commercially available motor drives.

1.2 Background

The Illini Formula Electric RSO participates in the Electric category of the Formula SAE competition and over the past few years has been gradually getting more competitive. In the competition year of 2021, the team aims to progress their design to a 4-wheel drive design with independently controlled PM motors in each wheel. This requires motor drive units to convert DC power from the battery to 3-phase AC power for the motors. The drive inverters used by competitors are too heavy and expensive.

1.3 Physical Design

As seen in Figure 1, a Texas Instruments control card will be attached to a control board which sits above the power stage and the entirety of this represents a single motor controller. Four such identical motor controllers will be placed within a single heat-sink enclosure.

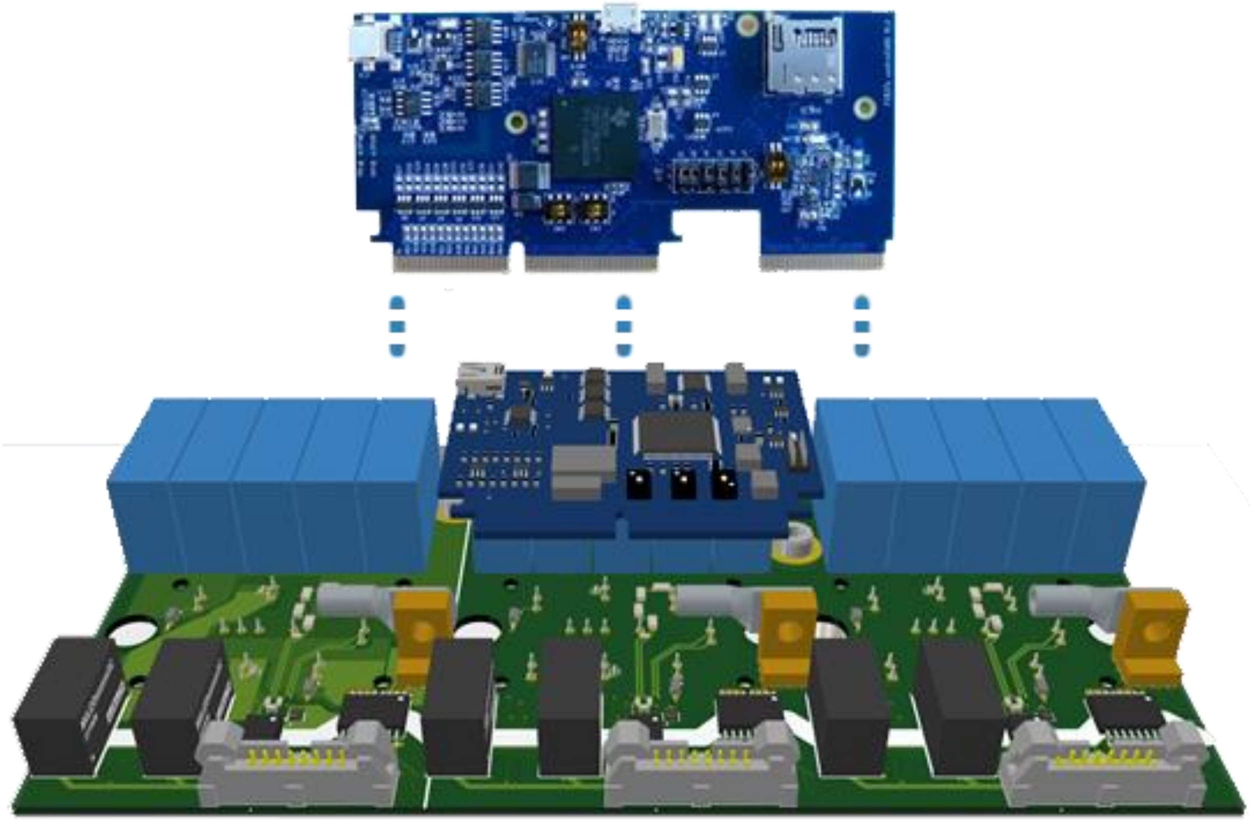

Figure 1: Texas Instrument Control Board connection to the main PCB

1.4 High-Level Requirements

Our first high-level requirement is that our drive inverter has a maximum power dissipation of less than 350W per module at peak output power of 35kW. Competitors' and commercial solutions generally used in our event have drive inverters that dissipate 1500W or more, requiring water cooling. Our design aims to be air cooled and use a heatsink. Hence, the restriction on dissipation at 350W or less.

Second, the inverter must have a small volume occupied. Our race car has very little space designated for the inverter, and primarily due to the limited heatsink area, we require the drive inverter to fit in an 200x100x20mm volume. Our plan is to use multiple stacked PCBs to keep the volume occupied as small as possible. This is hard to achieve in a high voltage design where very specific clearance and creepage constraints are defined.

Our final high-level requirement is that the weight of our drive inverter module is less than 6 kilograms. Despite using a heavy heatsink, the system weight is expected to be lower than competitor's drive inverters and commercial designs that typically weigh more than 8 kilograms without any cooling and potentially over 12kg including cooling. Weight is an important factor when it comes to designing a vehicle for Formula SAE.

Even reducing the vehicle's overall weight by just 2%, which has a significant effect on the competitiveness and performance of our electric race car.

2 Design

The overall vehicle design, as seen in the following figures, will consist of 4-motor controllers, but to constrain the scope of the class we will only build one and replicate the same 4 times in the vehicle. This single inverter contains 2 primary components, the power stage, and the control board, these are described below.

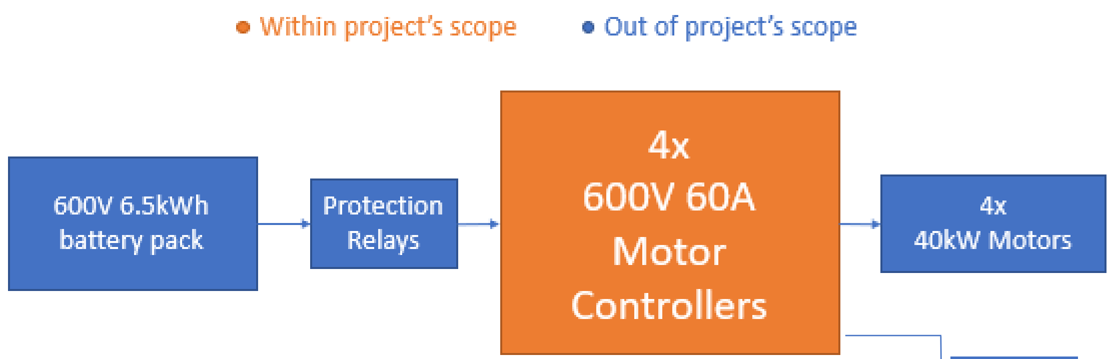

Figure 2: Overall block diagram representation

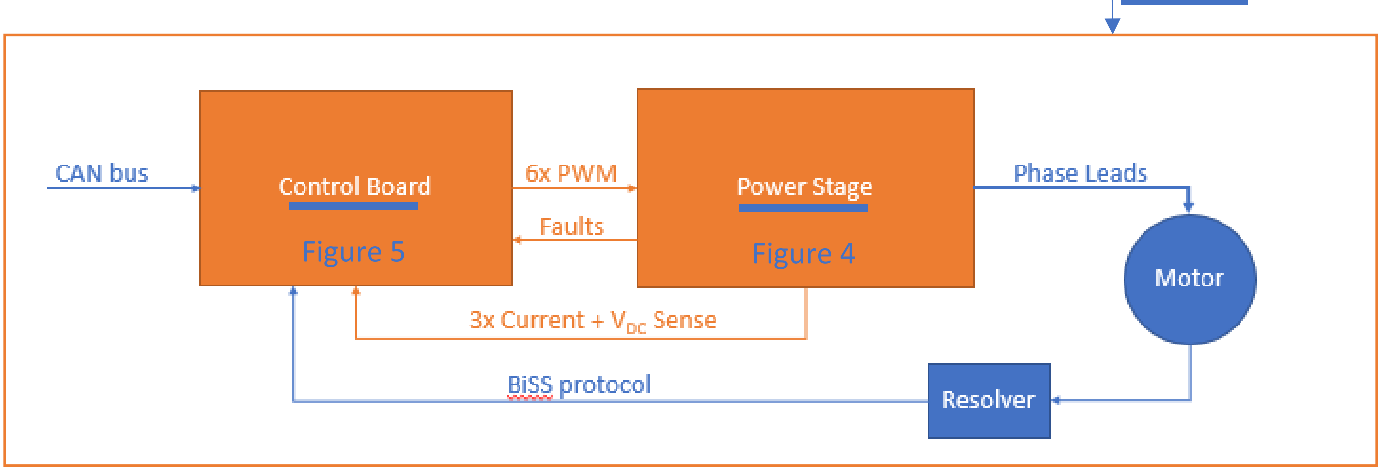

Figure 3: Single Motor Controller block diagram representation

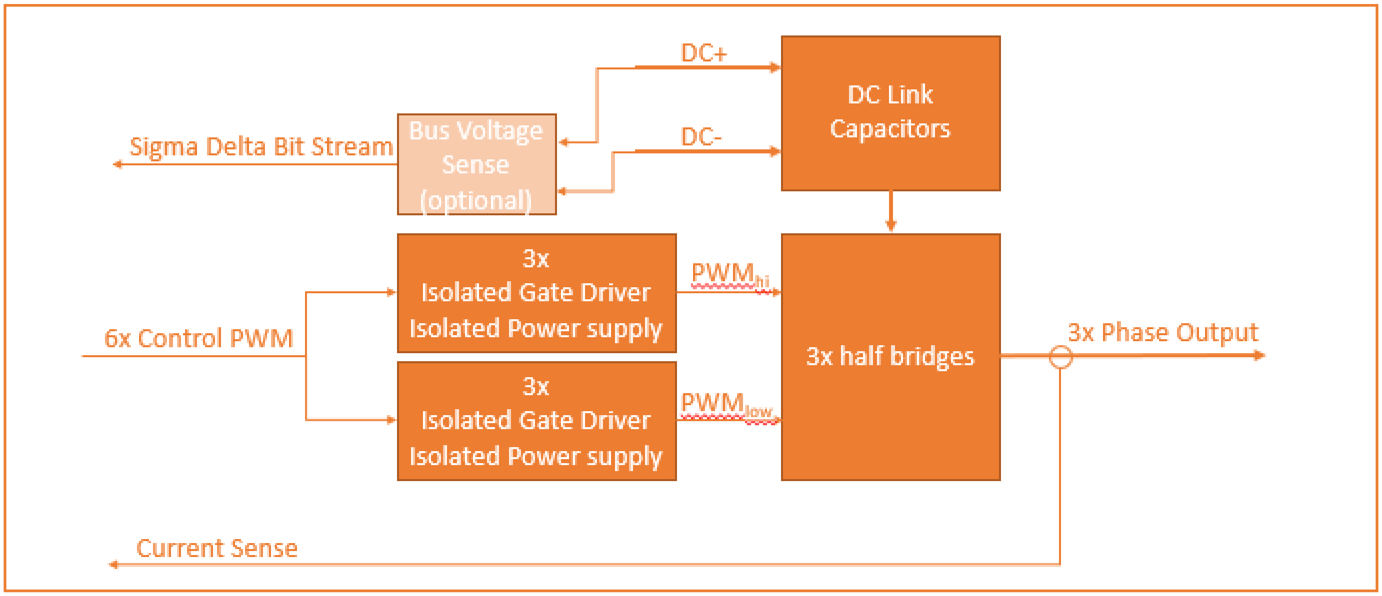

Figure 4: Power Stage block diagram representation

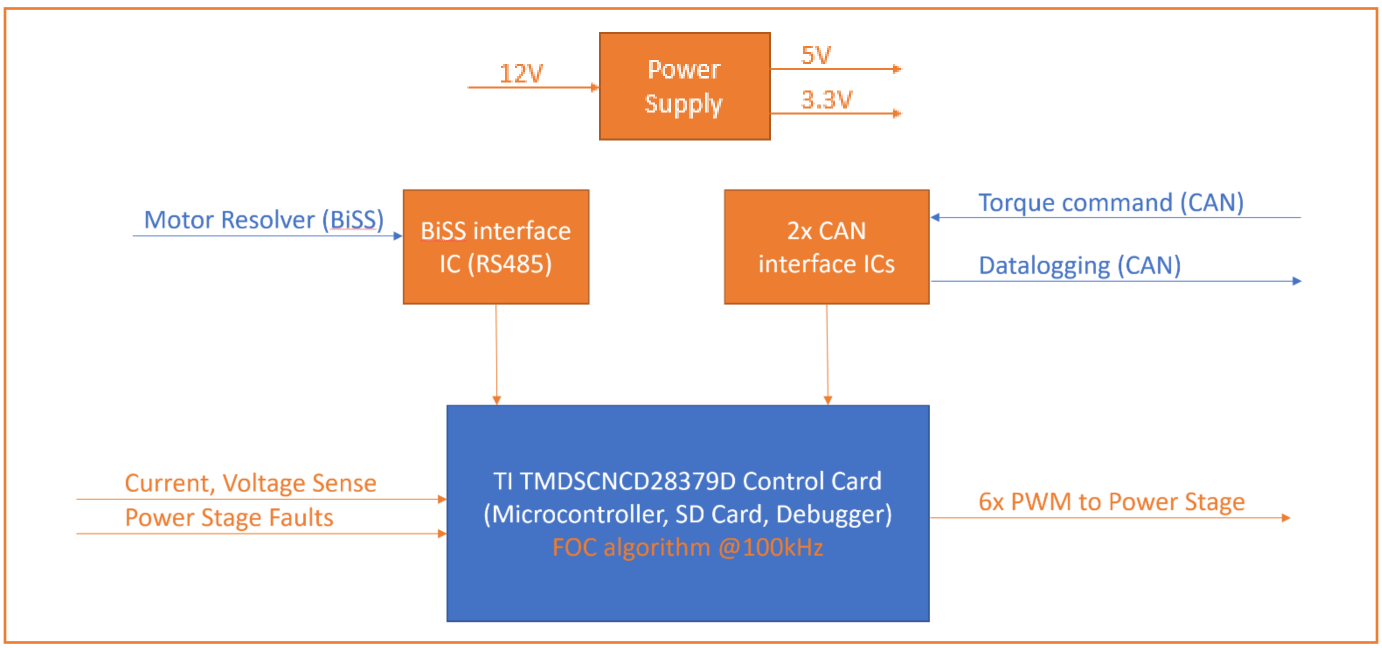

Figure 5: Control Board block diagram representation, which includes Texas Instruments' Control Card featured in Figure 1

2.1 Motor Controller (Figure 3)

The device in question that takes converts 600V_{dc} from the vehicle's battery and converts it to a 3-phase AC output at up to 62A_{rms}.

2.1.1 Power Stage (Figure 4)

The power stage contains all high voltage and high current paths of the inverter. Each phase leg consists of DC link capacitors, a Silicon Carbide (SiC) MOSFET half-bridge, gate drivers, isolated gate drive power supplies and DC bus voltage sensing which will only be populated on one of the phases. Further, current sensing of all phases and temperature sensing of each module is also present

2.1.1.1 DC Link Capacitors

Since capacitor inductance and layout loop inductance is hard to estimate even if using simplified methods as described in [5], capacitors similar to those used in [2] were selected and placed in an approximately similar layout. A total bus capacitance of all 3 phases of 45uF was chosen to provide sufficient decoupling at 50kHz PWM frequency while minimizing volume. If switching losses are higher than expected, there is enough capacitance margin to allow the PWM frequency to be reduced to 30kHz.

2.1.1.2 Isolated Gate Driver and Isolated Power Supply x6

Each of the 6 MOSFETs in the inverter, 2 per module are driven by the same gate driver IC (UCC21750). It supports important features like desaturation detection and interlocked PWM inputs which prevent MOSFET damage in failure situations as described in [1]. Further, a miller clamp and analog to PWM converter allow for a more compact design. The power supply is a 2W isolated module optimized for SiC gate drives (MGJ2 series) which is rated for sufficiently high CMTI, just as the gate driver.

2.1.1.3 Half Bridges x3

A low inductance Infineon half-bridge module (FF11MR12W1M1P_B11) is used to implement the phase legs. This allows for compact temperature sensing, excellent thermal performance, and lower overall costs.

2.1.1.4 Bus Voltage Sense

A multi-resistor divider and isolated sigma delta converter (AMC1336) allow for compact and noise free measurement of the DC bus. The input analog filters are configured to attenuate switching noise, and the isolated 5V supply is provided by a low-noise high-PSRR linear regulator from the low-side gate driver voltage.

2.1.2 Control Board (Figure 5)

The control board is responsible for communicating with the motor resolver and the CAN bus and based on those inputs as well as sensed signals from the power stage, execute the FOC algorithm on a microcontroller safely.

2.1.2.1 Power Supply

We require 12V, 3.3V and 5V busses for the different ICs on the board such as our gate drivers, isolated power supplies and interface controllers. However, we will only have a 12V supply to the board, hence the power supply section generates these additional 2 rails for low power components.

2.1.2.2 BiSS Interface IC (RS485)

BiSS is a RS485 based signaling protocol designed for high speed motor resolvers that is very noise immune and accurate. An RM44x resolver is placed on the motor shaft that interacts with the control board over this protocol. An RS485 Tx/Rx interface is used for this and will be implemented on the board using the circuit from [7].

2.1.2.3 CAN Interface ICs x2 (MCP2562)

Each CAN (Controller Area Network) IC will handle data transmission from the CAN bus that is accessed by other components on the car. With this setup, one of the MCP2562 chips will take in torque commands sent on the bus and communicate them to the microcontroller. The other IC will output data for the vehicle's datalogger to store critical parameters, status history, potential error codes and crashes.

2.2 TI TMDSCNCD28379D Control Card

The control card from Texas Instruments will strictly be used for the software side of the project. We plan to program it with a Field Oriented Control algorithm that operates with double-sampling at 100kHz. It takes in motor rotor position from the BiSS interface and current and voltage data from the power stage. Using the torque command from the CAN bus, the algorithm will generate six pulse-width modulation signals that are sent to the power stage to drive each MOSFET.

3 Ethics and Safety

In following IEEE's 7.8 Code of Ethics, Section I Policy 1 "To hold paramount the safety, health, and welfare of the public... ", there are two concerns our group shall address.

As of Fall 2020, the University of Illinois @ Urbana-Champaign has provided guidelines for preventing the spread of COVID-19. All members of this project group will follow CDC recommended safety guidelines to prevent the spread of COVID-19, and receive testing for the virus twice a week, per the Student guidelines provided by the University [8]. In-person work will be limited to "as necessary". All other work will be completed remotely in order to maximize social distancing.

As this project will involve working with high voltage electronics, our project members will follow best practices as outlined in IEEE STD 4-2013 "IEEE Standard for High-Voltage Testing Techniques". Any work done with active power electronics will be done with at minimum 2 people present for testing for safety purposes. [9]

As work on this project corresponds to progress on a component of a vehicle owned and operated by Illini Formula Electric, all work contributed by parties outside of the three listed in this project proposal will be properly attributed. This will be in accordance to IEEE's 7.8 Code of Ethics Section I Policy 5 "... and to credit properly the contributions of others; "

Finally, in accordance with Section I Policy 6, "... to undertake technological tasks for others only if qualified by training or experience, … ", all tests will be conducted in the Electrical and Computer Engineering Building labs in which project members are certified and trained to work in. Members will make every effort to be familiar with any power electronic testing equipment and its operation before conducting testing.

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