Electrical Safety and Power Management in Scaled-down Electric Vehicles

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Abstract

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Electrical Safety and Power Management in Scaled-down Electric Vehicles

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Abstract—This paper details the intricacies in the design of power supplies for varied voltage and current requirements in scaled-down electric vehicle platforms. It includes the development of protective circuits safeguarding electrical and electronic components from overvoltage, undervoltage, reverse voltage, inrush current, and surge current. Furthermore, the paper explores a sophisticated sensing module designed for continuous monitoring of battery and cell voltages. The circuits are implemented and tested on a one-tenth-scale electric vehicle, DEFT, operating with a 6-cell LiPo battery.

Index Terms—Circuit Protection, Battery Health Monitoring, Scaled-down Electric Vehicle

I. INTRODUCTION

SCALED-DOWN electric vehicles (EV) present a controlled testing environment for the assessment of autonomous driving algorithms, hastening their development while diminishing the perils related to trials involving full-sized vehicles. Noteworthy examples of scaled-down platforms are - AutoRally [1], MIT RaceCar [2], and F1tenth [3]. The vehicle platforms are powered by LiPo batteries, which, despite being an efficient power source, present specific challenges. One prevalent concern is spiking while connecting LiPo batteries to devices with input capacitance, such as bypass capacitors. This phenomenon generates an inrush current, which poses the risk of causing damage to the battery and any connected devices. Voltage surges due to battery malfunction can also permanently damage connected devices exceeding operational limits. Additionally, prolonged use may result in permanent damage to the LiPo battery if any of its cells drops below 3V. Crucially, when using a LiPo battery, careful attention must be paid to ensure correct polarity during battery connection, as devices sharing a common Ground line may be damaged in the event of reverse polarity. We present the conceptualization and design of three essential components:

1) protection circuits to safeguard electrical and electronic devices from surge current, inrush current, reverse voltage, overvoltage, undervoltage,

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2) a robust battery health monitoring system to prevent LiPo battery damage due to a drop in cell voltage below the safe limit and

3) reliable and robust power supplies for scaled-down EVs.

We translate our circuit designs into tangible and functional printed circuit boards (PCBs) customized for our indigenously designed and developed one-tenth-scale electric vehicle DEFT [4], shown in Figure 1. Subsequently, we validate the circuits by running DEFT and verify the reliable and consistent operation of the circuits.

Fig. 1. DEFT - A One-Tenth Scale Electric Vehicle

DEFT’s [4] electrical and electronic components rely on four critical DC supply lines - 3.3V-1.5A, 5V-7A, 7.4V-2.6A, and 22.8V-7A. To meet these power requirements, we employ a 6-cell 22.2V LiPo battery with a continuous discharge rate of 25C. We design step-down circuits to generate the 3.3V, 5V, and 7.4V supply lines while directly sourcing the 22.8V line from the battery. We meticulously select buck converter ICs and design the step-down converter to ensure maximum efficiency, minimal space utilization, enhanced heat dissipation, and improved reliability. Additionally, we employ bypass capacitors and resistors to fine-tune the circuit’s stable and optimized performance. This holistic approach, combined with a thoughtful PCB design, guarantees robust functionality and underscores the novelty of our design.

We discuss the details of the voltage supply design and the compatibility with other hardware platforms in Section II. We describe the protection circuits and the battery voltage monitoring in Section III and Section IV, respectively. We detail the tests and observations for the designed circuits in Section V. Finally, we conclude the paper in Section VI.
II. Power Supply

In DEFT [4], the driving motor requires a minimum of 18V for DEFT’s operation. We directly connect the battery output to the motor controller [5], which distributes the power to the driving motor. With the Nvidia® Jetson Nano™ single-board computer (SBC) and other peripherals operating at 5V demanding a peak current of 5A and 2A, respectively, the 5V supply line requires step-down with a maximum output current higher than 7A for reliable and lasting operation. We utilize a 7.4V supply to power both the microcontroller and the steering servo motor in DEFT. By providing 7.4V, we simultaneously meet the recommended criteria of input voltage for the Dynamixel XL 320 servo [6] and ensure compatibility with the Arduino DUE microcontroller’s operational range [7]. We set the supply voltage to 7.43V, slightly above the desired level to compensate for voltage losses in PCB traces and wires, and the maximum current output to 3A to accommodate the 2.6A peak current required by these devices. The 3.3V line powers sensors and low-power electronic devices and has a maximum current requirement of 1.5A.

An illustration of the power supply lines and their associated components is shown in Figure 2. We discuss the design of the 5V, 7.4V, and 3.3V supply lines in the following sections.

![Fig. 2. Schematic diagram of the power supply lines in DEFT](image)

A. 5V Supply

We design a DC-to-DC converter that steps down the output of the battery and provides an output of 5V-8A using an LTM®4613 buck converter module [8]. The designed circuit is illustrated in Figure 3.

To attenuate noise, we use low ESR ceramic capacitors of 10µF at the input (VIN) and FET drain (VD) pins of the LTM®4613, respectively. The resistor divider with 51kΩ and 4.53kΩ creates an undervoltage lockout (UVLO) at 18.4V. To minimize ripple in the output voltage, we set the operating frequency to approximately 940kHz and use 188µF (47µF ×4) low ESR ceramic capacitor at the output (VOUT) pin. The 49.9kΩ resistor sets the operating frequency for the step-down converter. For accounting voltage loss in the PCB traces and wires, we set the output voltage a little higher than 5V, ensuring the voltage is below the maximum voltage rating of all devices powered at 5V. We use a 13.3kΩ feedback resistor with 0.1% tolerance, which sets the output voltage to 5.11V.

B. 3.3V and 7.4V Supply

To optimize space and ensure stable output voltage, we use a dual-output LTM®8024 buck converter module [9] to obtain 7.43V-3A and 3.32V-3A power supplies. The designed circuit is shown in Figure 4.

![Fig. 3. 18.4V to 36VIN, 5.11V at 8A Design with 940kHz Frequency](image)

![Fig. 4. 10.5V to 40VIN, 7.43V-3A and 3.32V-3A Design with 1.2MHz Frequency](image)
To design a protection circuit using a LTC® current, overvoltage, undervoltage, and reverse voltage, we connect directly to the battery from surge current, inrush conditions to be approximately 17\,\text{V}.

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III. Protection Circuits

To safeguard the electrical and electronic components connected directly to the battery from surge current, inrush current, overvoltage, undervoltage, and reverse voltage, we design a protection circuit using a LTC®4365 IC [10]. The designed circuit is shown in Figure 5.

Under normal conditions, the current source at the GATE pin activates the MOSFETs, allowing current flow from the battery to the load circuits. From SPICE simulations of the DC-DC converter circuits and the motor controller’s datasheet, we found the maximum current required under all operating conditions to be approximately 17.6\,\text{A}. Also, the drain-to-source breakdown voltage of the MOSFET should be kept above the maximum voltage rating of the battery to accommodate the voltage ratings of the LTC®4365 and utilize its voltage protection features. To meet all the criteria, we use a dual n-Channel Infineon IPG20N06S4L-26 MOSFET [11] rated with a continuous rating of 60\,\text{V}-20\,\text{A}.

Undervoltage protection is initiated if the voltage at the UV pin falls below 0.5\,\text{V} while overvoltage protection is initiated when the voltage at the OV pin goes above 0.5\,\text{V}. We use a voltage divider with a 10M\,\text{k}\,\Omega, a 71.5k\,\Omega, and a 205k\,\Omega resistor with 0.1\% tolerance to implement undervoltage, and overvoltage cutoffs of 18.58\,\text{V} and 25.06\,\text{V}, respectively.

In cases of reverse polarity, the MOSFET with its Drain connected to the output voltage turns OFF, and no current flows from the battery to the motor controller and the voltage regulators. To ensure surge protection under normal conditions and reverse voltage, we use a bidirectional TVS diode at the V\text{IN} pin. We use a TI TVS2701 TVS diode [12], which has a standoff voltage of 27\,\text{V}.

The inrush current while connecting the battery to the PCB is limited by adding a capacitor at the GATE pin of the LTC®4365. The relation between the GATE capacitor and the inrush current is given as

\[
I_{\text{irush}} = \frac{C_{\text{load}}}{C_{\text{gate}}} 20\,\mu\text{A}
\]

Using a 0.01\,\mu\text{F} capacitor at the GATE pin, we limit the inrush current to 0.574\,\text{A}, which is low enough to cause any damage.

The output of the LTC®4365, V\text{s}, serves as the supply voltage for both the DEC 50/5 motor controller and the voltage regulators. As an added layer of protection against voltage and current surges that may affect the individual circuits, we employ a combination of a unidirectional TVS diode and a fuse across the input voltage pins of the motor controller and the voltage regulators. We opt for the TI TVS2700 TVS diode [13] with a standoff voltage of 27\,\text{V}. For the motor controller, we incorporate a fast-blow 8\,\text{A} fuse, while the LTC®4613 and LTC®8024 utilize resettable fuses with 3\,\text{A} hold current - 5.2\,\text{A} trip current, and 6\,\text{A} hold current - 12\,\text{A} trip current, respectively.

To safeguard the microcontroller, SBC, servo motor, and other devices powered by the 5\,\text{V} and 3.3\,\text{V} supply lines against potential voltage and current surges, we implement a combination of fuses and Zener diodes with breakdown voltages a little higher than the respective supply voltages.

We implement the voltage regulator circuits discussed in Section II and the protection circuits along with the communication and interfacing circuits detailed in [4] in a single printed circuit board (PCB), namely the Motherboard of DEFT. The motherboard PCB is illustrated in Figure 6.

These protection circuits are versatile and easily applicable to other scaled-down platforms with minor adjustments. By selecting appropriate resistor divider values for undervoltage and overvoltage protection, along with suitable TVS and Zener diodes for voltage surge protection and fuses rated to specific current surge requirements, these circuits can be seamlessly adapted to diverse platforms.

IV. Battery Health Monitoring

Monitoring both the overall battery and individual cell voltages is imperative for ensuring the vehicle’s operation remains within the safety limits. A critical safety concern arises as LiPo batteries can suffer permanent damage if any of the cell voltages drop below 3\,\text{V}. Although DEFT incorporates undervoltage protection set at 18.6\,\text{V}, we cease operation before any individual cell voltage approaches 3.3\,\text{V}. This precautionary step becomes necessary because when a cell voltage hovers near 3\,\text{V}, a sudden, substantial current draw can lead to a precipitous drop below the 3\,\text{V} threshold, causing irreversible damage to the battery.

To monitor the cell voltages, we first connect each line of monitoring both the overall battery and individual cell voltages is imperative for ensuring the vehicle’s operation remains within the safety limits. A critical safety concern arises as LiPo batteries can suffer permanent damage if any of the cell voltages drop below 3\,\text{V}. Although DEFT incorporates undervoltage protection set at 18.6\,\text{V}, we cease operation before any individual cell voltage approaches 3.3\,\text{V}. This precautionary step becomes necessary because when a cell voltage hovers near 3\,\text{V}, a sudden, substantial current draw can lead to a precipitous drop below the 3\,\text{V} threshold, causing irreversible damage to the battery.

To monitor the cell voltages, we first connect each line of the balance connector with buffers designed with rail-to-rail OPAMPS such that no current is drawn from any individual cell. Then, the buffer lines are passed through differential amplifiers with a gain of 0.5 to obtain the individual cell voltages. For monitoring the overall battery voltage, the battery power terminals are connected to a differential amplifier of gain 0.1. The circuitry used for the differential amplifiers is shown in Figure 7. For measuring cell voltages, differential...
amplifiers are configured with \( R_1 = 12\, \Omega \) and \( R_2 = 6\, \Omega \), while the differential amplifier for measuring battery voltage employs \( R_1 = 100\, \Omega \) and \( R_2 = 10\, \Omega \). We choose the gains 0.5 and 0.1 to ensure the amplifier output voltages remain below 3.3V as DEFT’s microcontroller is 3.3V tolerant.

We use TI OPA4991-Q1 [14] for the rail-to-rail buffers, TI INA157 [15] amplifiers for the cell voltage measurements, and TI INA106 [16] amplifier for the battery voltage measurement. The INA157 and INA106 precision difference amplifiers were selected for improved amplifier accuracy due to the on-chip resistors compared to external resistors with parasitic impedance. The power supply to all the OPAMPs is provided by the protected supply line \( V_i \). We implemented the circuits on a PCB from which the amplifier outputs are connected to the Motherboard and interfaced with the microcontroller.

V. TESTS AND OBSERVATIONS

We conduct simulations and real-time tests on critical circuits within DEFT to validate their performance and adherence to design specifications. We ran DEFT involving the components illustrated in Figure 2, testing its functionalities, features, and limits running for over 350 hours spread over 5 months. The autonomous motion of the vehicle on a circular trajectory, recorded with DEFT’s front stereo camera, can be visualized at doi.org/10.6084/m9.figshare.24312073. We highlight the following features:

1. Stability and output of the 5V supply with the LTM®4613: We simulate the circuit in Figure 3 in LTspice® with a 0.7Ω load to verify the output voltage and current for an input voltage of 23.4V. The simulation output is shown in Figure 8. It is observed that the circuit provides a stable output of 5.11V-

2. Stability and outputs of the 7.4V and 3.3V supplies with the LTM®8024: We simulate the circuit in Figure 4 in LTspice® with a 2.48Ω load across the 7.43V output, and a 2.2Ω load across the 3.32V output. The simulation output is shown in Figure 9. Figure 9 verifies that the desired voltage and current outputs are obtained with the designed circuit. During real-time testing, the output voltage at channels 1 and 2 are found to be 7.41V and 3.31V, respectively.

3. Evaluation of UVLO protection and inrush current limiting capabilities with the LTC®4365 circuit: We conducted tests on our protection circuit, incorporating the LTC®4365, to evaluate its performance for undervoltage protection and inrush current limiting. Our findings demonstrate that the designed circuit effectively severs the power supply when the battery’s voltage dips below 18.67V, thereby confirming DEFT’s undervoltage protection feature. The slight discrepancy between the theoretical value of 18.58V and the actual reading of 18.67V can be attributed to parasitic impedance within the PCB traces and

**Fig. 6.** The left and right images show the top and bottom view of the motherboard, respectively

**Fig. 7.** Differential amplifier used for obtaining equivalent cell voltages; \( i = [1, 6] \) and \( V_{0i} = \text{GND} \).

**Fig. 8.** SPICE simulation of the circuit in Figure 3 with a 0.7Ω output load. 7.3A and reaches steady-state in 0.2 milliseconds. During real-time testing, we found the output voltage to be 5.08V, and all devices connected to the 5V supply work seamlessly, which validates our design.

**Fig. 9.** Figure 9 verifies that the desired voltage and current outputs are obtained with the designed circuit. During real-time testing, the output voltage at channels 1 and 2 are found to be 7.41V and 3.31V, respectively.
inaccuracies in the resistor divider’s resistances. Nevertheless, this difference is negligible and serves the intended purpose. Furthermore, no spark is generated while connecting the LiPo battery to the motherboard PCB, which validates the inrush current protection feature in DEFT, as described in equation 1 in Section III.

4. Functioning of the designed battery and cell voltage sensing system: For reading the analog signals, we select the 12-bit resolution in Arduino DUE. We charged the battery to 24.1V, and measured the battery and cell voltages while DEFT was in motion. The measured voltages for the circular trajectory are plotted in Figure 10. Figure 10 shows that the battery voltage is around 24V, and the cell voltages are around 4V, which is approximately the same as the actual values. This validates the working of our designed battery and cell sensing module and the measurement strategy.

VI. Conclusions

In this paper, we present the design and development of power supplies, protection circuits ensuring electrical safety, and a battery health monitoring system for a scaled-down (one-tenth scale) electric vehicle named DEFT. We verify our designs through SPICE simulations and engineer PCBs to realize the circuits. We validate the functionality and features of the designed circuits through real-time testing on DEFT. With minor modifications in the circuits, the designs can be adapted to other scaled-down EV platforms.

Our efficient power supply and electrical protection systems, along with the LiPo battery sensor, contribute to a safe and reliable testing platform, extending the lifecycle of DEFT’s electrical and electronic components. Overall, these systems present optimized solutions for scaled-down electric vehicle platforms, emphasizing efficiency and reliability.

References