A Go-cart as an Electric Vehicle for Undergraduate Teaching and Assessment

Bill Heffernan, Richard Duke, Richard Zhang, Paul Gaynor and Michael Cusdin

Department of Electrical and Computer Engineering
University of Canterbury
Christchurch, New Zealand

Abstract— **To complement the traditional undergraduate lecture-based power electronics course material, the University of Canterbury has introduced a design and build assignment which focuses on motor control and the issues of interfacing to the mechanical world. Stimulation of the students' interest is achieved by using electric go-carts and holding a series of performance trials which pit teams of students against each other. Each team mark is assessed through a laboratory inspection, a written report, a peer assessment mark and an outdoor trial. As well as stimulating the students' interest in power electronics, this assignment provides them with a range of "real world" practical design experience.**

Keywords-power electronics education; student project; motor drive

I. INTRODUCTION

The traditional lecture-based course is good at testing the basic factual knowledge of theoretical power electronics. However it has several drawbacks; it often does not emphasise the importance of real-world techniques for acquiring new knowledge, and making decisions when faced with incomplete or contradictory information. Nor does it adequately address the further requirements of identifying and applying key practical engineering concepts, such as the significance of stray self and mutual inductance in real circuit layouts. To master power electronics a student should demonstrate a proficiency in [1]:

- factual knowledge
- knowledge of engineering procedures
- the ability to identify key concepts
- the ability to acquire new knowledge
- judgement to use incomplete or contradictory information

The 48 lecture Year 4 undergraduate power electronics course, which follows on from an introductory 24 lecture Year 3 course, is very much an applications focussed course. For the past 15 years students have undertaken a practical dc-dc converter design and build assignment involving a model solar powered car [2] in the first half of the course. About one third of the course content of the Year 4 course is related to motor drives and control, and historically this part of the course has been assessed through highly specified laboratory experiments. The success of the solar powered car assignment and positive feedback from the students prompted academic staff to consider the possibilities of a second design and build assessment. Most students understand the concepts of a car, and with the high profile of electric vehicles the decision was made to mould the assignment around the idea of an electric go-cart.

II. GO-CART DETAILS

The off-road vehicle chassis (Melrose 80RT) was purchased from a commercial distributor [3]. Each cart is driven by a 4hp 24V permanent magnet motor which is supplied from a 75A-hr 24V lead-acid battery source. Five of these carts have been constructed. Because of the significant currents involved in this assignment the students are presented with a cart which has the battery, motor, power circuits, MOSFET drivers and high-level protection circuits already provided as shown in Fig. 1.

The electrical drive schematic diagram Fig. 2 shows an overview of the electrical hardware provided on each go-cart. This diagram summarises the motor connection, the power

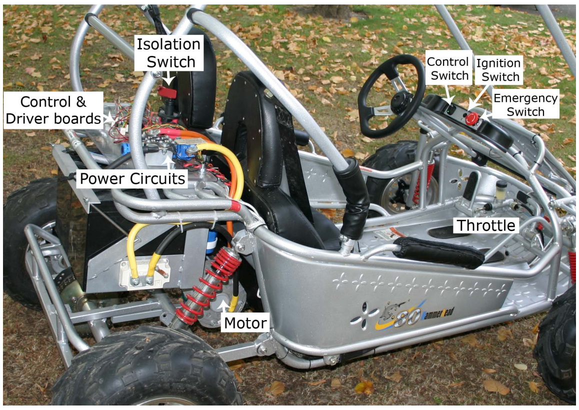

Figure 1 Go-cart

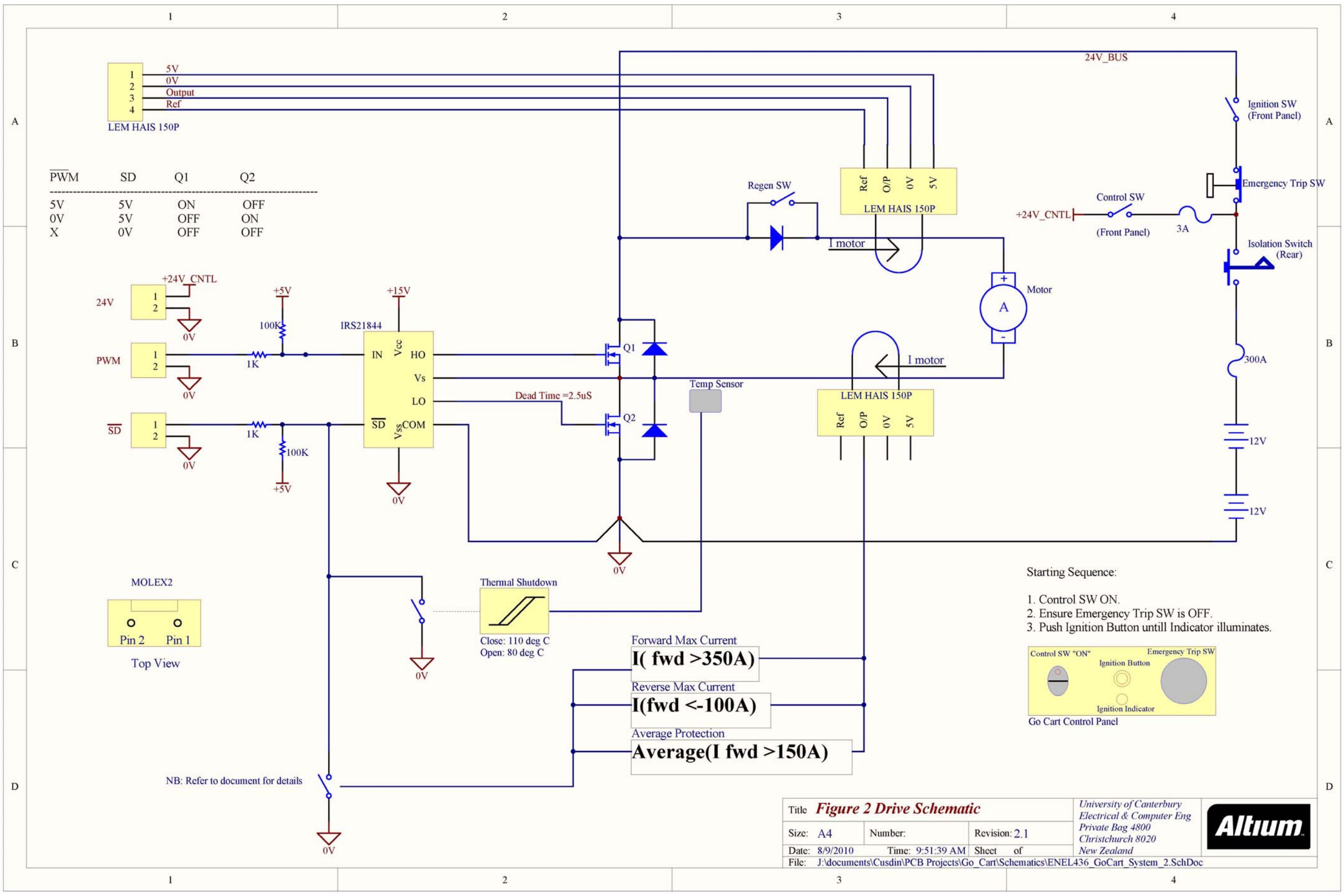

Figure 2 Go-cart drive schematic

electronics block including the robust MOSFET drive interface, the high-level protection, the various switches and the points of interconnection for the students.

A. Motor

A 4hp 24V permanent magnet motor is presently used, but the carts have been designed so alternative motor types could be used in the future. The motor driveshaft is coupled to the rear wheels directly via a 10:1 chain link.

B. Power Circuits

At the heart of the power circuits are two MOSFETs connected in series as a synchronous dc chopper topology. The motor is connected across the top MOSFET. In reality each of these MOSFETs is actually a parallel combination of two IR2804S-7PPbF MOSFETs (see Fig. 3), rated 40V and 160A each. 53mF of dc bus capacitance and six transient voltage suppressors (TVSs) are included to clamp the MOSFET voltages and protect them against the voltage spikes inherent in the circuit.

The power circuits are not connected directly to the batteries. Instead, the connection is made via several features that have been added to enhance utility and student safety (Fig. 1):

- An isolation switch with a removable key which physical isolates the electrical system of the go-cart from the batteries.
- A control power toggle switch, which switches the power delivered to all control circuitry.
- An ignition switch, which operates the main high current capacity contactor controlling the connection of the batteries to the power circuits.

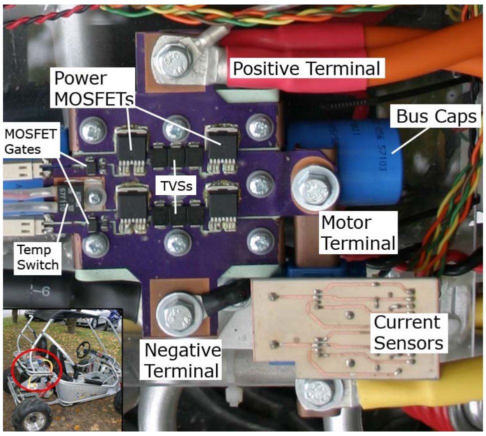

Figure 3 Power circuits

- An emergency shutdown switch which opens the previously mentioned main contactor, isolating the power circuits from the battery.
- Thermal shutdown protection.

C. *Current Sensors and Overcurrent Protection*

Two LEM HAIS 150-P current transducers are installed to provide independent feedback of the current flowing into and out of the motor. One of these is used to provide the current information for the high-level current protection and the second one is provided for student use.

To ensure students can work safely, and to protect the motor and power circuits, multiple levels and techniques of overcurrent protection circuitry have been included:

- A 300A fast-acting semiconductor fuse provides top-level protection.
- Instantaneous forward overcurrent protection limits the peak current to under 350A. This level of protection activates whenever the current exceeds this 350A threshold. Once activated the circuit pulls the IRS21844 MOSFET driver shutdown pin low and only releases it when the current falls below 300A. This hysteretic action allows a momentary current of around 300A to flow for a few cycles.
- Average forward current protection limits the average current to 150A by using an integrating ampere-second mechanism. The average current can exceed 150A by xA for a period of y seconds, such that $xy \approx$ 100As. (e.g. an average current of 180A for 3s, 300A for 600ms, etc.) If the 100As is exceeded the circuit pulls the IRS21844 MOSFET driver shutdown pin low for about 7s.
- Instantaneous reverse overcurrent protection operates in the same way as the instantaneous forward overcurrent protection, but limits the peak reverse current to less than 100A.
- Ultrafast MOSFET desaturation protection set at around 1000A.

The coordination of the forward current protection is summarised in Fig. 4.

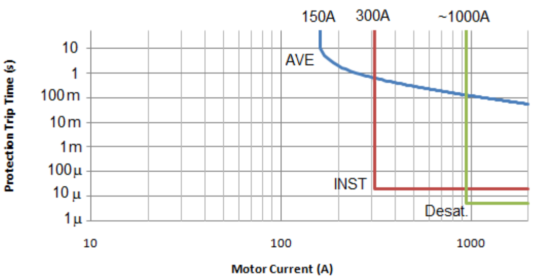

Figure 4 Forward current protection coordination

D. *Throttle*

The original throttle has been modified to operate a 10kΩ linear potentiometer. A connection to the throttle potentiomenter for the students is provided in the form of a three-pin Molex connector. To protect the motor in a stall situation a normally open position switch has been installed on the brake pedal and student controllers must be able to detect when the brake pedal has been depressed and immediately disconnect their drive circuitry.

E. *Driver Board*

A driver board, indicated in the Fig. 5 block diagram, which uses the IRS21844 driver chip to interface with the MOSFETs in the power circuits has been developed. This driver board also contains numerous protection circuits (Fig.2) which will shut down both MOSFETs to protect them and the motor from harm. So as not to permanently damage the lead-acid batteries, undervoltage protection is included on the driver board. Over frequency protection to cater for the situation when the switching losses exceed the MOSFET rating is also included.

The driver board is uncontrolled; it does not know what to do with the power circuit to make the motor work. It must be told exactly what to do with each MOSFET by an external control board which the students produce as an output of this assignment. The Student Control Board Fig. 5 has access to the four connections indicated in Fig. 2 plus the throttle output:

- The PWM signal and the shutdown control $\overline{SD}$, which combine to control the state of each of the MOSFETs via the IR21844 gate driver.
- The 24V dc power supply from which all power supplies are derived.
- LEM sensor connections which provide the current information for the protection.

III. TEAM-BASED PROJECT

The scope of the assignment, with a time-frame of only six weeks for project completion, and the fact that students are undertaking this assignment while four other courses and their Year 4 honours project is running, demands that the assignment is well-structured as a team-based project. The students usually work in groups of three to ensure that they all experience some

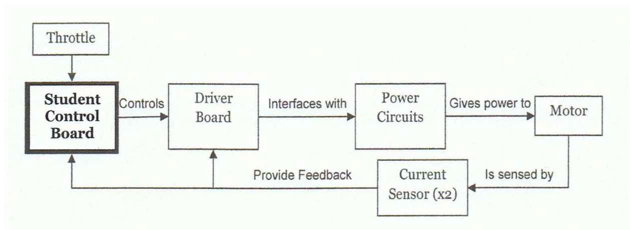

Figure 5 Go-cart drive block diagram

aspect of design, decision-making and teamwork. A team-based project means that the students also gain experience in managing a project, and communicating effectively with others. It has been found that having a team of three enables the students to bounce ideas off each other and to build on each others strengths. If the student teams are too large then there may be the situation in which some of the team members may not fully participate and learn from the assignment.

Most of the teams require guidance in how they should proceed with their project. This is achieved by covering relevant material in lectures which parallel the assignment, by providing assignment-specific tutorials and by utilising postgraduate students as tutors in the laboratory. At all stages the students are given the knowledge to understand the issues as they occur so that they may solve the problems themselves, rather than just being given the solutions directly.

The students choose their own team-mates and as a consequence the academically able and capable students often choose to work together. Similarly some other groups are often made up of only average to below-average students. No attempt is made to "equalise" abilities across the groups. With this philosophy the more capable student groups challenge the individuals within that group, pushing their collective output well beyond their individual outputs. This enables these teams to spend more of their time refining and optimising their design for the final trial. On the other hand, the average to below-average student teams are usually more reliant on postgraduate tutorial and laboratory technical support. Because of their lack of understanding and practical experience their progress is often impeded and they might not have a fully functional prototype by the end of the assignment.

Because of the expected wide range of achievement the overall marking schedule clearly identifies particular goals giving all groups the opportunity to score appropriately according to their abilities and achievements. The details of how the assessment is organised is discussed in Section V.

IV. Student Project Details

By way of example, the following overall statement of the assignment goal was given to the 2010 class. "Your ultimate goal is to produce a fixed frequency current mode controller using the UC3843 current mode control chip which will win the go-cart reliability trial at the end of the assignment.

You face the following constraints on your designs. These constraints parallel real life limitations that actual electric vehicle designers face:

- Forward motor current must not exceed 350A.
- Reverse motor current must not exceed 100A.
- Average forward motor current must not exceed 150A.
- No MOSFET can be switched faster than 5kHz (from combined SD and PWM action)

If at any of these constraints are exceeded, the go-cart will shut down for 5 seconds, ruining your chances of winning the reliability trial."

To help the student teams plan their attempts at the assignment and to produce a well-defined graduation of achievement for the allocation of marks at the laboratory review the following suggested sequence of activities was given to the students.

- Produce PWM using the UC3843 chip. Your signals must have:
  - Voltage swing of 5V (referenced to ground),
  - Rise and fall times <1μs,
  - Switching frequency of 2.5kHz ±10% for your PWM signal,
  - Overall switching frequency from both PWM and $\overline{SD}$ of <5kHz.

- Make the PWM controllable via the throttle. A normally open position switch has been installed on the brake pedal so that you can detect whenever the brake is operated. Your control system must be able to detect when the brake pedal has been depressed and immediately disconnect the drive circuitry. Reset this function by releasing the brake. When the Emergency Trip pushbutton switch is pressed it should disconnect all power to the motor and drive circuitry. When the switch is reset it should automatically re-enable the drive circuitry and put the cart in a safe ready-to-drive state. To earn full marks in this section your motor should not rotate when the throttle is not depressed.
- Close the control loop. This requires you to sensibly use current feedback provided to you by the LEM sensor in your controller design. Your controller should be stable - your PWM should stay reasonably constant for a fixed throttle position and a fixed load. There should be no significant oscillations in any of the control signals.
- Implement fixed frequency current mode control.
- Successfully limit average forward current to <150A, peak forward current to <350A and reverse current to <100A. Note that you will only get full marks for this requirement if your controller actually attempts to push the average forward current >100A.

A range of bench-top test-stations are provided for the students to test their designs before graduating to the pont of applying their control boards to an actual cart:

- A driver board connected to a low power unloaded dc motor for initial testing.
- A driver board connected to a low power dc motor which has been loaded to mirror the rotational inertia required to drive an actual cart.
- A low current multi-turn current sensing circuit to test overcurrent protection.

Each driver board contains appropriately scaled protection circuits and indication LEDs which indicate when any of the four constraints on current or switching frequency are violated.

Each year when projects like this are offered to each new class, the challenge is to find a set of requirements which make the project different to recent previous years. Following are typical examples which the students may be required to implement:

- Use standard analogue voltage PWM throughout the assignment
- Implement a digital PWM solution
- Implement a regenerative braking system
- Implement a cruise control system.

V. ASSESSMENT

This particular assignment is worth 25% of the total course assessment. Four components make up this 25% assessment; a laboratory review worth 10%, a peer assessment mark worth 3%, a group written report worth 12%, and a group bonus mark of up to 5% awarded for the car's performance at the trials (Fig. 6). Thus there is the possibility of a group scoring 30% if they can manage to do extremely well in all aspects of the assessment

A. Laboratory Review

Typically this assignment runs over a six-week period and at the conclusion of week five each group is subjected to a laboratory review of their progress. They meet with the lecturer in the laboratory, bringing with them their hardware, a copy of their circuit diagram and their design notes. As part of the review each group's control philosophy is questioned and the functionality of their controller fully bench tested.

The full 10% contribution from the laboratory review can only be achieved if the group has attempted to solve the complete problem. For example the marking schedule for the 2010 class assignment was as follows:

- Produce PWM using the UC3843 chip (2%).
- Make the PWM controllable via the throttle (1%).
- Close the control loop (2%).
- Implement fixed frequency current mode control (3%).
- Successfully limit average forward current to <150A, peak forward current to <350A and reverse current to <100A. (2%).

Figure 6 Go-cart trial

The weightings of the various component parts of the laboratory review assessment are carefully chosen so that even the average achieving groups have the opportunity of scoring a pass mark. In general the philosophy for the allocation of marks means that the first half of the marks are relatively easy to obtain, but the additional marks are progressively more difficult to achieve, with the groups having to put in an increasing effort to obtain each incremental mark. Questions can be directed to each individual group member and even though a group mark is awarded for the laboratory review it is quickly obvious whether or not each individual understands what they are doing and the relative contributions of each group member can be readily assessed. This information can then be correlated against the peer assessment mark (discussed in sub-section B) provided by the students in the final determination of the overall assignment mark for each individual.

B. Peer Assessment

To ensure a fair work distribution, each student group are asked to determine the tasks that each member has overall responsibility for, and to provide a one page summary of individual responsibilities by the end of week one. The expectation is that the majority of the design work on each task should be completed by the group member assigned it.

At the end of the assignment, after the submission of the report, each group member is asked to revisit and update the original summary document submitted in week one. In this updated version they are each asked to give each of the team members (including themselves) a mark out of 3 on how they contributed to the overall group effort. Each mark must be justified with comments to be considered by the lecturer. Any student not submitting their Peer Assessment Mark for their team will not be eligible for this component.

C. Report

At the conclusion of the assignment a single report for the group is due. Whilst this is a group report, it should contain individual sections describing the various functions of your controller and the expectation is that each of these sections of the report will be written by the group member with the primary responsibility for that function. The instructions the students are given is that each report should have a formal structure, the type that you would produce for your boss as if you were working as a power electronics R&D engineer in a company. The emphasis on the assessment of the written report is on documentation of the design process, the group's understanding of that process, and the evaluation of their design. It should contain such things as:

- A discussion of the motor speed control as a whole, e.g. how it works, its suitability and possible improvements.
- Individual explanations of circuit design, decisions made during design and finally circuit operation (with block diagrams, graphs, scope captures etc.).
- Throughout the assignment a number of design decisions will have been made on the basis of

incomplete or non-existent information. An explanation is expected of how these decisions were dealt with.

- A discussion of the features that may have been added in trying to win the race.
- A discussion of the overcurrent protection philosophy and its operation.
- An explanation of the shutdown/start up philosophies.

D. Trial

The trials are a vital part of the success of this assignment; they are an important motivator and publicity tool. Trials take the form of a reliability time trial where each group gets one practice lap and one timed lap. Reliability is measured by the number of times the 5 second penalty shutdown operates (refer to Section IV). Bonus marks for 2010 were allocated according to a simple schedule as shown in Table 1.

Using the bonus mark idea for the trials has proved to be a useful psychological ploy with the students. Their enthusiasm for the trials is largely driven by two factors; their desire to beat their peers and the perception that by doing well in the trial they can significantly improve their overall mark for the assignment. The reality however is that only one group may actually achieve the full five bonus marks and the majority of groups score only one or two marks.

Table 1 Trial bonus marks schedule

Bonus mark	**Requirement**
5	Fastest time with no shutdowns
4	2nd fastest time with no shutdowns or Fastest time with least number of shutdowns
3	3rd fastest time with no shutdowns or 2nd fastest time with least number of shutdowns
2	Complete a timed lap
1	Complete a partial lap

VI. Summary

Student feedback on this assignment has confirmed that they believe time spent on the assignment has been a very worthwhile educational experience. Students have often commented that it is the opportunity to bring some reality to the academic material, presented in lectures and the textbooks, that they enjoy. In teaching and course surveys students have consistently rated this assignment highly as a learning experience.

Gregson and Little [1] identify ten characteristics of a good contest:

- is safe
- requires increasing factual and procedural knowledge
- requires exercising engineering judgement
- fosters creativity
- incorporates significant course material
- provides success commensurate with care in design
- permits many strategies with levels of success
- does not require significant infrastructure
- is easy to understand with simple scoring
- should be a spectacle

The authors believe that they have achieved all of these characteristics in this assignment. The trial is a vital part of the success of this assignment, it is an important motivator and publicity tool. As race spectators Year 2 and 3 students see power electronics as being challenging and a fun learning experience, and want to be part of it. There is absolutely no doubt in our minds that this annual teaching project has had a very positive influence on student numbers and on their motivation to learn.

References

[1] P.H. Gregson and T.A. Little, "Using Contests to Teach Design to EE Juniors," IEEE Trans. on Education, vol. 42, no. 3, pp. 229-32, August 1999.

[2] R. Duke and S. Round , "Converter Design for a Model Solar Car," Proc. 10th International Conference on Power Electronics and Motion Control, Cavtat, Croatia, 7 pages, September 2002.

[3] http://www.melrosemotorsports.co.nz/offroad-karts.html