Consolidating Design Experience Through Product Development.

Chris B. Effiong¹, Ronny Howard² and Allen Crittendon³

Abstract – Engineering education starts with the formal training in the physical sciences and mathematics, which are usually completed in the first three or four semesters of a four year undergraduate program. Engineering curricula are designed to lead the students from the basic sciences background to engineering body of knowledge through lecture and laboratory exercises. Over the years, the acquisition of formal engineering design skills by undergraduate students has been emphasized in addition to the development of soft skills. To make sure that these skills are acquired at the time of graduation, most undergraduate engineering programs have adopted the Capstone Design Project (Senior Design project) as a requirement for graduation. In this paper, a senior design project, which consolidates design experienced through product development, is presented.

Keywords: Capstone Design, dc-dc converter, topology, MOSFET, and Pulse width modulation.

INTRODUCTION

The acquisition of formal engineering design skills by undergraduate students has been emphasized by employers of engineering graduates. In addition to design skills, soft skills such as oral presentation, documentation, time management, leadership, etc. are required in the modern work environment. To make sure that these skills are acquired at the time of graduation most undergraduate engineering programs have adopted the Capstone Design Project (Senior Design project) as a requirement for graduation [Dutson, 3].

The students at the University of Tennessee at Martin, Tennessee are required to take a senior design project that extends over two consecutive semesters. The intent of the project is to close the design experience loop and thereby assess the expected outcomes of engineering design in the program. The students in consultation with their faculty advisors choose a project that will provide the platform to demonstrate all the expected skills acquired through lecture and laboratory exercises. This is a formalized process that culminates in the development of a tangible product to satisfy some accreditation requirements [ABET, 1].

The project undertaken by the students was the design and development of a prototype dc-dc converter for automobile industry. The specifications were set to meet industry standards. The product development process included product research, design and construction, documentation, and presentation. The results of the analysis and evaluation of their product show promise for future development of an efficient, low weight, low cost and, compact dc-dc converter for specific use in automobiles.

MOTIVATION FOR THE PROJECT

The automobile industry is transitioning from 12/14 volts to 36/42 volts, which is similar to the transition from 6-volts battery to a higher energy 12-volt battery in the 1950’s. Today, the automobile industry is facing the same situations that the industry faced in the 1950’s. This new transition has developed the need for a low cost, compact DC-DC down converter. The demand for increased power and the support of 42V systems is being driven by enhanced vehicle

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performance, improved fuel economy, emissions reduction, and new electronic systems, such as electric power steering, electromechanical breaks, onboard navigation systems, entertainment systems and electrically controlled air conditioning and heating systems. These vehicles offer higher power consumption ratings and some even feature an AC voltage outlet. The development of a low cost, compact DC-DC down converter can be beneficial to many consumers and would have a large market. It is projected that the production of 42V vehicles will reach about 13 million units by year 2010 [Intertech, 6]. However, in an attempt to save money, manufacturers would like to be able to continue using the lower voltage components in these newer vehicles. Thus, the need for development of a dc-dc converter has been recognized. The development of a dc-dc converter will provide the platform to consolidate engineering design experience for undergraduate students.

**PROBLEM STATEMENT AND DESIGN SPECIFICATIONS**

The motivation given the preceding section led to the selection of a design problem that will provide the platform to demonstrate the skills acquired through courses and also satisfy ABET design requirements. The problem statement and performance specifications are given next.

**Problem Statement**

Automobiles will make a transition to a 42 V electrical system soon, but many 12 V parts will still be used. There is need to design a power interface for the new 42 V automotive electrical systems with external network control. The objective is to design and build an efficient but very inexpensive power electronic converter for 42 V to 12 V, to serve older components of the electrical system. Cost is the biggest issue, followed by size.

**Design Specifications**

The specifications given for the development of a prototype are as follows:

(a) Input range is +30V to +60V dc.
(b) Output should be +12 V minimum and +14 V maximum, with good control capability, and maximum output power up to 100 W.
(c) Input/output isolation is not required.
(d) The total volume not to exceed 150 cm³.
(e) The total cost for parts (based on high-volume production) will not exceed $10.
(f) The converter should be capable of remote control through a shared RS-232 or other standard serial port and protocol.
(g) The converter should respond to commands only when it receives an identifying string, then it should turn on or off as requested.
(h) It must be demonstrated with a 12 V headlight or other power-consuming vehicle component.

**DESIGN APPROACH**

This section presents the design approach that was taken to satisfy the design specifications of the product. The approach consists of the following steps: topology selection and design evaluation.

**Topology Selection**

The high efficiency, compact space and cost requirements were the limiting factors on topology selection. By using a standard design table [Brown, 2], the choice was narrowed down to a boost converter. The most efficient and most effective topology investigated was based on a pulse width modulation (PWM) integrated circuit (IC). Within this segment there are several ways to construct a DC-DC converter. Figure 1 shows a PWM/MOSFET arrangement which includes a transformer. This method was abandoned early on because of space considerations.
Figure 1. PWM/MOSFET setup with a transformer

Figure 2 shows a very similar design to Figure 1 the difference is that it does not have a transformer. This topology showed promise initially because of its simple design. After much experimentation this design was abandoned because of a lack of IC documentation.

Figure 2. PWM/MOSFET setup without a transformer

Figure 3 depicts the design selected for the project. This topology still uses the PWM/MOSFET arrangement but it is all combined with one chip. This design offers high efficiency and compact construction, as well as low cost.

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Design Evaluation

The original intent was to create the device in its entirety in a simulation program such as PSPICE or MULTISIM and to test for all conceivable scenarios of operation. This was impossible mainly because of the lack of models from manufacturers. Simulink, a program inside Matlab, had a simple pulse width modulator block, but it did not have the ability to test or even accurately construct the topologies shown earlier in Figures 1, 2, and 3. Faced with the simulation limitations, the next best option was to combine simulation with experimentation.

Two major functional parameters of the design are voltage and power outputs of the device. Given these parameters, a choice has to be made on how to obtain the correct voltage conversion and also provide the current level to meet the power requirement. After several experiments, a MAX5033 based system was chosen. This IC has a PWM and a pair of MOSFET’s combined into one chip. The circuit can produce the desired output voltage, but at a maximum of 0.5 A at approximately 12V, which results in a about 6 watts output power, well below the required power output of 100 Watts. At 100 Watt of output power, the load current requirement is about 8.33A. To achieve this level of current flow a Darlington pair transistor (DLPT) was selected. In order for the DLPT to operate properly it had to be in the common-collector configuration and it had to have resistors attached to the base and emitter for proper operation.

The final consideration in the design phase of the project was the wireless transmitter/receiver (transceiver). Size was the major constraint in the choice of transceiver to be used. Several options were considered. The choice made was based on the security consideration that, the transceiver was capable of having a code set on each device that would only allow operation if the code was sensed at the receiver. The output of the receiver on the device has to be connected to the on/off pin of the MAX5033 through a low pass filter to provide isolation from other circuit components. The remote transceiver has to be compatible with the setup of the device transceiver. The choice narrowed down to a Radiotronix transceiver with an encoder/decoder pair. The transceiver subsystem operated at 433.92 MHz, which is within FCC requirement for a variety of wireless applications [FCC, 5]

The wireless TTL/CMOS activation needs a simple a high or low signal. The receiver’s output is original code that was previously set on the transmitter. The wireless transmitter can be set to put out a set of highs and lows that are also set on the receiver. This meets the security requirement of the specifications since only this signal can activate the receiver. Once the receiver senses the transmission it sends out the same signal given by the transmitter to the decoder. This signal is sent to a small transistor switch for the PWM. The PWM has an on/off pin that, if grounded, will shut down the chip, thus shutting down the entire circuit.
**DEVICE CONSTRUCTION**

The different subsystems of the device were integrated as shown in Figure 4. The construction of the device consisted of two major parts namely, the circuit enclosure and the printed circuit board (PCB).

**Circuit Enclosure**

The original intent was to design and fabricate an enclosure to fit the PCB layout. It was decided to find a prefabricated case in order to save time and money. The prefabricated enclosure is shown in Figure 5. This layout set the dimensions for the PCB, such that it could fit snugly in the case. It was found out that a fairly large heat sink was needed to mount the DLPT on. One reason for choosing this enclosure was for its metallic base. However, the base was made of a very thin aluminum. It was decided that the base should be made of a heavier metal (18ga steel) so as to provide large heat absorbing capacity and thereby provide a medium to conduct heat away from the circuit elements. An appropriate size of heat sink was chosen to handle the amount of heat that will be generated by the DLPT.

**Printed circuit board (PCB)**

The printed circuit board (PCB) was designed using ExpressPCB software. There were several options for how to layout out the board. The most basic was a two layer board which meant there were two layers of traces, one on the top and one on the bottom. The other option was a four-layer board. The MAX IC required a ground plane so the four-layer option was chosen. The converter circuit layout including the transceiver is shown in Figure 6.

![Figure 4. DC-DC Converter Circuit Layout](image)

![Figure 5. Converter Enclosure](image)
with all the different subsystems annotated in the circuit layout. There was no in-house facility to construct the PCB. The developed circuit was set up for PCB production by ExpressPCB. The PCB layout is shown in Figure 4 in actual scale of the board.

![Figure 6. Printed Circuit Board](image)

**TESTING AND RESULTS**

After the converter circuit components were soldered onto the circuit board and placed in the enclosure, a number of tests were conducted to validate the performance of the device. Two of the major tests done were the current load test and thermal load test, and both are reported here.

**Current Load Test**

Two current load tests were performed. A 20 Watt load with unknown value of resistance and a 30Ω load were used in the tests. The results from the current load test are shown in Table 1. From the table it is seen that the voltage regulation deteriorated as the input voltage was increased beyond 40 volts.

![Table 1. Current Load Test](image)

**Thermal Load Test**

For a proper thermal test to be conducted, maximum operating temperatures for all components were gathered. With this information maximum test temperature was to be held to 70°C. A soil oven (with digital readout) was used to
perform the thermal test. The regulated output voltage was monitored along with the current through a 30Ω load, the
temperature, and receiver operation. The results of this test are shown in Table 2. All specifications were met.

Size and Cost Evaluation
The internal volume was less than 150 cm³, which was the maximum value allowable. Cost specifications required a
per unit material cost to be ten dollars or less. For this circuit topology, a minimal number of components were
utilized. Where applicable, sections were purchased as modules. For example, the Maxim IC eliminated several
external components and increased efficiency. The receiver module came ready to be affixed to another board.
Combined individual component prices made module purchases less costly. Quotes were taken for 5000 and 10,000
pieces. To make a mathematical estimate, an exponential best fit was performed [Eshenbach 4].

<table>
<thead>
<tr>
<th>Temperature °C(°F)</th>
<th>Regulated Output Voltage (volts)</th>
<th>Output Current (mA)</th>
<th>Receiver Operability (YES/NO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.7(71)</td>
<td>12.3</td>
<td>390</td>
<td>YES</td>
</tr>
<tr>
<td>37.8(100)</td>
<td>12.365</td>
<td>395</td>
<td>YES</td>
</tr>
<tr>
<td>43.3(110)</td>
<td>12.50</td>
<td>399</td>
<td>YES</td>
</tr>
<tr>
<td>48.9(120)</td>
<td>12.63</td>
<td>403</td>
<td>YES</td>
</tr>
<tr>
<td>54.4(130)</td>
<td>12.67</td>
<td>405</td>
<td>YES</td>
</tr>
</tbody>
</table>

estimates for 10,000 pieces were thought to be more than enough to force the per unit material cost below ten
dollars. As Figure 7 shows this estimate was wrong. Thus, the number of units required for a material cost of ten
dollars or less was 29,135.

CONCLUSION
The product development reported here took the students through the iterative process of design and development.
A broad knowledge base was necessary for the completion of the project. Knowledge gained from courses such
electronics (digital and analog), circuits, communications, Materials, Engineering Methods and Design, and
Electromagnetics were utilized. Computer aided design tools, which included EWB MultiSim, MATLAB, and

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AutoCad were used in simulation and analysis. Other skills such as budgeting, teamwork, time management, documentation, and presentation were all honed during the process to consolidate the students design experience.

The product developed satisfied the functional specifications given to the students. From economic considerations, the budget and per unit cost were achieved. The size requirement was also met. Voltage regulation or control surpassed an initial parameter of +/- 10%. The Percent of voltage regulation achieved was 4.8%. The current handling capability was less than specified and the maximum power output of 100 watts could not be achieved. The remote control operates properly. The most important objectives were met in that the converter would cost less than ten dollars per unit if a minimum of 29,135 pieces were manufactured and the converter has a total volume of 150 cm$^3$.

From the experience gained the students were able to make recommendations as follows: (a) research combinations of integrated circuits, combine the Schmitt trigger and the J-K flip flop into a single module (b) Develop ways of using a 2-layer board to reduce overall cost. In other words, the goal is to produce a system on a chip.

REFERENCES


BIOGRAPHICAL INFORMATION

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