Design of a Laboratory Power Supply – a Capstone Research Project

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Abstract—This paper discusses the design and construction of a power supply that utilizes a hybrid topology of a switching and linear voltage regulator in order to achieve a regulated voltage and current output that has low ripple, low voltage current stability, and overall consistent efficiency. The supply is designed for use in commercial laboratories or by avid electronic hobbyists. Key results are that the power supply will provide multiple output voltages as follows: A single regulated output with adjustable output voltage and current as well as three additional adjustable output voltages each capable of delivering up to two hundred milliamps. These additional outputs are commonly used for circuit testing and evaluation. The goal of this work is to design and produce a product that can be used in many applications.

Keywords—power supply, regulated voltage, linear regulator

1. INTRODUCTION

Power supplies are devices used to provide electrical power to a broad range of equipment, test circuitry, and components in a commercial laboratory or a home workshop setting. In general, these devices are used to deliver a range of direct current (DC) output voltages that are fixed or adjustable. While the commercial and personal use of these supplies is similar in nature, the commercial industry can demand the need for very high voltage and current capabilities in power supply units that are manufactured for specific purposes. For the scope of this project, a low voltage power supply with current and voltage capabilities that are within the common range of those found in a standard laboratory setting will be developed.

The typical laboratory setting presents conditions where various DC voltages are required simultaneously in order to test and/or evaluate circuitry. An integrated circuit containing op-amps, digital ICs, and microprocessor chips can create a demand of +15VDC, +/-12VDC, and +5VDC. This often results in increased costs as multiple power supplies are needed to accomplish a single task. In addition, the dedicated use of a second lab supply for low current applications such as providing housekeeping supplies or partial circuit isolation testing is both excessive and wasteful.

The intention of this project is to create a lab supply that can be used as an out of the box solution for testing conditions commonly encountered in either the commercial industry or a home workshop setting. The overall goal of the design is to create a single laboratory power supply that will be able to furnish the end user the ability to handle most of the common applications regularly encountered in the industry without the need for multiple lab supplies. The laboratory power supply will provide reliable DC voltages to be used in many applications. It will be enclosed in a metal housing that contains a front panel user interface for output voltage and current setting adjustments. The power supply will be similar in size to a typical bench top supply.

The rest of the paper is organized as follows. Section 2 discusses the design specifications. Section 3 presents the technical approach. Section 4 presents the formal description of the proposed system and hardware implementations. Section 5 presents the results of the work with concluding remarks in section 6.

2. DESIGN SPECIFICATIONS

- The laboratory power supply will convert a single phase 120 VAC input in order to achieve all output voltages.
- The single adjustable output voltage will be 0 to 30VDC with 0 to 2A current capability.
- The housekeeping output voltages will be +/-9 to +/-12VDC, and +3.3 to +5VDC of at least 200 mA.
- The laboratory power supply will utilize a pulse width modulator (PWM) to implement the switching portion of the hybrid power supply topology.
- The user will be provided local control of the power supply through front panel potentiometers to control the output voltages and current setting.
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- LCD meters will provide the user with voltage and current display for the single adjustable output while bi-color LEDs on the front panel will provide operation status of each output.

For clarification purposes, the overall design specifications are shown in Table 1.
# Technical Approach

This section contains the technical details that will be utilized to implement the design of the Lab Power Supply. For clarity purposes, the power supply will be divided into seven segments: linear regulator, switching regulator, intermediate DC bus generation, control loop, negative voltage generation, fault detection and protection circuits. The circuits derived were for simulation purposes only and do not always reflect the actual components selected for the design; however major components are identified and discussed. The design approach was to begin from the output of the power supply and work back towards the AC input. The power supply’s main output is designed around a hybrid circuit consisting of a switcher and a linear regulator. This topology was selected to benefit from the good efficiency of the switching regulator (and therefore minimize the need for heatsinking and cooling) and the low output ripple and noise and excellent dynamic characteristics of the linear regulator.

## The Linear Regulator

The linear regulator model used for simulation purposes is shown in Figure 2. It works on the principle that one is able to control the output voltage at the emitter of the power transistor Q1 by manipulating the voltage at its base. Connected to the non-inverting input of the op-amp U1A, called the error amp, is the voltage reference, V2. Connected to the inverting input of the error amp is the midpoint of a voltage divider (R1 and R2). The error amp will react to any difference between its two input voltages by adjusting its output voltage which is connected to the base of the NPN transistor: when the error amp drives current into this transistor’s base, it allows current to flow from collector to emitter, and that transistor in turn pulls current from the base of the pass transistor. This setup allows an op-amp capable of only driving a few milliamps to control several amps through the pass transistor. The highest output of the laboratory power supply is the single adjustable 0-30VDC, 0-2A supply. Based on this, the voltage divider network is designed with a 10:1 output voltage scale with a maximum scale reference voltage (V2) of 3VDC. For example, a reference voltage at V2 of 1VDC will translate to 10VDC on the output. The actual linear regulator selected to implement the Lab Power Supply was the LT3080. It is a low dropout, low noise linear regulator capable of delivering up to 1.1A and has an input voltage range of 1.4 to 40VDC and output voltage range of 0.4 to 32V. In order to meet both the maximum output current of the single adjustable output, two LT3080s will be used in parallel. In addition, the three housekeeping output supplies will be provided with the LM317 (positive outputs) and the LM337 (negative output) linear regulators.

## The Switching Regulator

The buck converter block (A1) in Figure 3 was utilized in place of an actual pulse width modulator (PWM) in order to conceptualize the design. A buck converter or step-down switch mode power supply can also be called a switch mode regulator. It provides high efficiency by utilizing a feedback loop that varies the pulse width based on the output load current. The typical application of a switching regulator is to provide a fixed regulated output that can handle various load conditions. The input to A1 in Figure 3 is the unregulated DC bus derived from the input AC/DC stage shown in Figure 4. The output of A1 is being controlled by the error amp U2A,
which is monitoring the voltage across the passive transistor of the linear regulator Q1. The error amp will try to maintain the same voltage at both input pins due to identical voltage dividers (R3 and R5, and R4 and R6), however, the voltage drop across D3 will ensure that there will always be a small delta across Q1. In order to achieve this, the actual switching regulator selected to implement in the Lab Power Supply was the LM2576. It is a simple 50kHz switcher capable of delivering up to 3.0A and has an output voltage range of 1.2 to 37VDC, which is able to meet both the maximum output voltage and current of the single adjustable output.

Figure 3: Buck Converter in Tandem with the Linear Regulator

The Intermediate DC Bus

The AC/DC converter designed for simulation purposes is shown in Figure 4. One criteria of a buck converter is that the input voltage must be higher than the desired output voltage. Since the maximum desired output voltage is 30 VDC, a step down power transformer (T1) with a 5:1 ratio was selected to provide a secondary voltage of 24 VAC. This AC voltage is processed by the full bridge converter and smoothed by the output capacitor C1. The DC voltage is approximately 32 VDC, which is calculated by the secondary AC voltage times the square root of 2 minus the voltage drops across both diodes. Since the linear regulator selected has a head voltage requirement of less than 0.4 VDC, the unregulated DC bus is more than adequate for this design. In order to meet the FCC regulations for EMI emissions as well as the UL and CE safety requirements, a commercial off-the-shelf AC/DC converter was selected. The converter provides a 36V regulated output with a 12% output adjustment. It can deliver up to 150W, has an efficiency of 86%, and has a maximum output ripple of 200mV. In addition, it has overcurrent, overvoltage and short circuit protection. It is both UL and CE listed.

Control Loop

For the lab power supply, the design approach shown in Figure 5 was implemented for the feedback loop in order to regulate the output supply. Since one of the drawbacks of the linear regulator is that any voltage drop across Q1 is dissipated in heat loss which translates to poor efficiency, an op-amp in the differential amplifier configuration (U5B) has the job of keeping the overhead voltage across the input and output of the linear regulator at a selected fixed voltage reference of V1. This allows the linear regulator to operate at a consistent higher efficiency state. Although the datasheet of the LT3080 linear regulator states that the overhead voltage in order to maintain output voltage regulation can be designed to be as low as 0.5VDC, a 2.0VDC reference was selected in order to provide plenty of margin.

Figure 4: AC/DC Power Conversion

Negative Voltage

An oscillator circuit with a negative charge pump on the output will be used to generate the negative output supply. A MIC4429 shown in Figure 6 utilizes the internal Schmitt trigger that uses the RC time constant as the input of the internal comparator circuit to create hysteresis by applying positive feedback to the non-inverting input of the amplifier. The configuration shown will be modified by setting the charge pump rectifier diodes and capacitors for negative voltage rectification. The actual circuit schematic is shown in Figure 7. The duty cycle was set to approximately 50% in order to maximize efficiency by setting the value of R38 experimentally.

Fault Detection

The output of the three housekeeping voltages are monitored for both undervoltage and overcurrent conditions. The output voltages are compared to a fixed reference voltage at the input of the comparators. During normal operation when the outputs are within 10% of the minimum adjustable
output voltage window, the output of the comparator provides the drive signal that will turn on the green LED. If the output voltage drops below 10% of the window either due to an output voltage failure or because it is in current limit, the output of the comparator switches states and the red LED illuminates. A schematic showing the negative output supply being monitored by a comparator is shown in Figure 8.

Figure 6: Oscillator Circuit

Figure 7: Negative Voltage Generator

Figure 8: Undervoltage / Overcurrent Fault Detection Protection Circuits

The following protection measures were taken for the Laboratory Power Supply:

- Overvoltage: All outputs are provided overvoltage protection with the use of zener transient voltage suppressors that are in parallel across each output.

- Overcurrent: Current limit for the 30 VDC output is user adjustable up to a maximum of 2A. The front panel provides a current limit preview setting for the main output labeled ‘I LIMIT PREVIEW’ via a momentary switch. Pressing the switch allows the user to set the current trip point by rotating the ‘CURRENT ADJUST’ knob of the front panel. The housekeeping supplies are internally limited to provide at least 200 mA. In addition, all linear regulators have built in short circuit protection.

- Thermal: A thermistor mounted to the chassis will provide temperature monitoring through a comparator stage that will shut down both of the buck converters when the temperature reaches 40°C. In addition, all regulators will use the power supply chassis for heatsinking.

- The mains input is protected with an in-line fuse that has a value of 2A.

- The power supply housing is connected to ground.

Figure 9 shows the complete schematic of the Lab Power Supply.

4. HARDWARE IMPLEMENTATIONS

The final product is a safe, reliable laboratory power supply that is user friendly and portable. It is comprised of the printed circuit board (PCB), the AC/DC converter, and the power supply housing.

PCB

After the electrical design was complete, the PCB Artist software was utilized to create the layout of the board. The software requires that a schematic of the design first be created prior to generating the Gerber files that contain the information for manufacturing the board. The goal of the design is to make the lab supply to have ease of manufacturing as well as testing. For this reason, three connectors were added that allow for quick connect and disconnect. For the project, the Digi-Key ‘Scheme it’ tool was used to create the actual schematic in Figure 9 because it has the advantage that it automatically generates a parts list which can be exported to an Excel spreadsheet. Although the Digi-Key schematic does not show the connector pin-outs, they are presented in Table 2.

Once the schematic is complete, the user is given the option to have the layout of the components as well as the trace width automatically selected or to do both tasks manually. Part of the design is to use the power supply steel housing as the heatsink so the linear and switching regulators were manually placed along the edge of the PCB board. The trace width for the maximum current of 2A and 1 ounce copper was calculated in order to ensure that the PCB would work for the design. An Excel spreadsheet containing formulas used by industry standards yielded a minimum trace width of ~30 mils for a 10°C rise. The default setting of the software is 15 mils (0.015”) so the high current traces were identified and set to a width of 50 mils.

Upon receiving the PCB board, a 100% point to point connectivity test was performed prior to soldering any components. Figures 10 and 11 show the completely populated board. Additional leads were added for three reasons. The first being that the LM339 comparator chip
selected (U16 of Figure 9) is an open collector IC that requires external pull-up resistors to a VCC source. The second reason is that a design feature of adding bi-color LEDs was implemented in the latter stage of the design that would add a visual recognition of output validity. The final reason for adding additional leads is that noise problems were encountered that affected the loop stability of the design. For this reason, a vector board was added to the design in order to isolate the switching circuits. The vector board was placed above the PCB using 1 ¼” standoffs. Figures 12 and 13 show the top and bottom sides of the vector board.

Figure 9: Final Complete Schematic
Table 2: Input and Output Connector Pin-outs

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<tr>
<th>PIN</th>
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**NC = NO CONNECTION**

5. Results

As part of the design process, an industry standard stress analysis was performed for all supply components to ensure that all remained within the test margins. Further, thermal analysis verified that no regulators required external heat sinks. Then, the laboratory power supply was fully assembled and an acceptance test datasheet was created to collect the data for the test plan that was developed in order to verify that the power supply met the design specifications. Figure 14 shows the fully developed final product.
6. CONCLUSION

The hybrid topology of a switcher regulator working in tandem with a linear regulator to produce a stable DC supply was materialized as part of this senior capstone design project. The voltage across the linear device for the main output was regulated to a constant low drop-out voltage for the entire range of the output in order to allow constant high efficiency. Although efficiency in a lab power supply is not particularly critical, this hybrid topology could be implemented in many power conversion applications that require high efficiency. The overall design which required only slight modification due to noise issue, provided safe, reliable outputs with overcurrent, overvoltage, and thermal protection in a package that has ease of manufacturability. The design met the desired goal of providing a power supply that can be used as an out of the box single solution to the demands encountered in the average laboratory and home workshop setting.

REFERENCES