

Redesigning the Power Supplies for the Theophilus Tower Light Show



Team Tower Power

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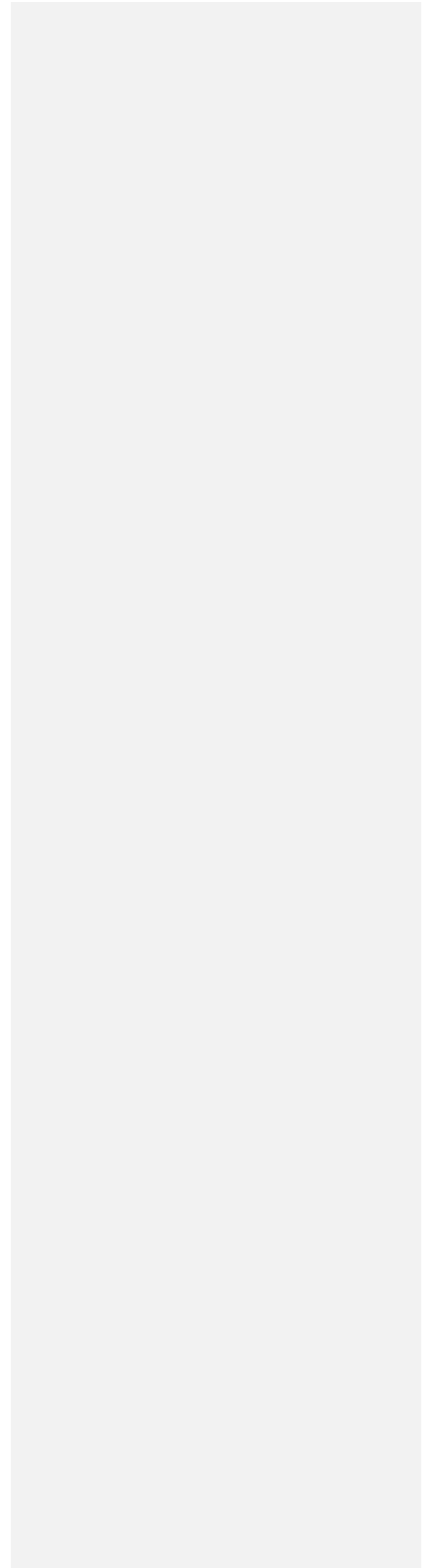
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Letter of Transmittal

Dr. Bob Rinker
College of Engineering – Computer Science
University of Idaho
PO Box 442336
Moscow, Id 83844-2336

December 5, 2013

RE: Tower Power Design Report

Dear Dr. Rinker,

Attached is the design report for the Tower Lights power supply.

We have outlined our design concepts considered thus far, and the solution we've decided to pursue. This report includes our schedule for next semester which will include testing and production.

Aside from our new solution concept, most of this information was in our design review that you attended earlier in the semester. Please review our new concept idea and let us know what you think.

Our team thanks you for the opportunity to be involved in such a fun project. We all learned a lot and look forward to delivering a finished product next semester. Have a great summer!

Sincerely,

Team Tower Power:

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Executive Summary

The goal of this project is to redesign the power supplies for the University of Idaho Theophilus Tower Light Show. The current supplies are inefficient and required large heat sinks due to the dissipation of excess power across resistors and transistors used in the supplies.

Since the LEDs drop different voltages depending on their color, three separate supplies are required. Each supply should be self-adjusting so that any supply can be used with any color LED. Each LED string requires 300 mA of current, so the supplies should be able to handle a maximum of 12 A of current since there are 40 parallel strings per supply. The new design should also reduce the input voltage to increase energy efficiency and reduce heat dissipated by the circuit.

Several different options were considered in order to meet each specification. These options are discussed in the Concepts Considered section of the report. The final solution that was chosen uses a buck converter chip to step down the input voltage. The output node of the chip is fed back through a string of LEDs in series and a control transistor into a sense pin. When a control signal is sent to the transistor, current flows through the LEDs to the sense pin node. The chip will adjust its' output voltage to meet the required load until the sense node reaches 1.22 V. To ensure that the required current is supplied to the LEDs, a load resistor of 4 ohms is attached at the sense pin node. This implementation reduces heat loss while also regulating the current through the LEDs.

Background

Since 2010 the University of Idaho Association for Computing Machinery (ACM) has put on several LED light shows by turning the Theophilus Tower into a giant pixel display. These lights shows are made possible by placing an LED bar in the window of each room on the south side of the Theophilus Tower. Each LED bar is connected to a power supply in the basement of the tower via the Ethernet connections in the building. The supplies are then connected to a microcontroller which controls the LEDs in order to create different light patterns on the face of the tower. The microcontroller, in turn, is controlled by one laptop located on the tower lawn.

Each LED bar is composed of three sets of tricolor LED's, Red, Green, and Blue (RGB). Each LED color has a separate current, so each LED bar has a line with three Red LED's in series, three blue LED's in series, and three green LED's in series. The LED's enable when they conduct current in the range of 270-300 mA. The red LED's drop approximate 2.5 V per LED, or 7.5 V per line, and the blue and green LED's each drop approximately 3.5 V, or 10.5 V per line.

The power supply currently being used is a constant voltage, constant current, power supply. It has a voltage output of approximately 16V on every line.

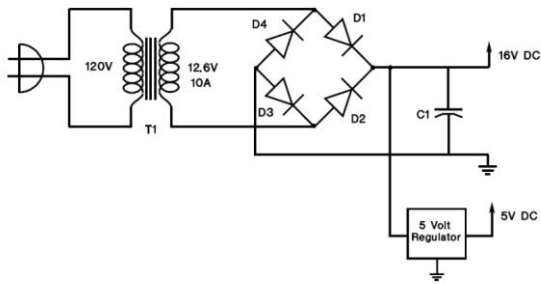


Figure 1: Voltage Regulation Circuit

Figure 1 shows the voltage transformer and regulation for the currently implemented power supplies.

There are 40 rooms on the South side of the tower, and three lines per room, so there are 120 total current channels. Figure 2 shows the constant current circuit currently used in the tower power supplies.

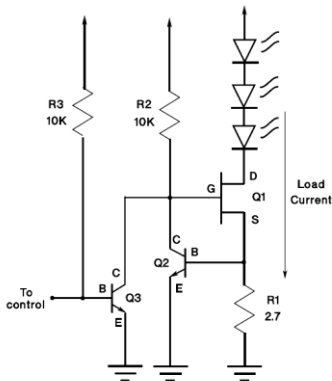


Figure 2: Constant Current Circuit

This constant current circuit is actually quite effective. Q2 is off, the voltage on the gate of Q1 is held high. This increases the load current. The load current will rise until the voltage at the base of Q2 is approximately .6V, at which time Q2 turns on and Q1 turns off. This balance means that the load current will be effectively constant, and the magnitude is determined by $.6V/R1$.

The control line of each string of LEDs is controlled by an Atmel AVR processor. For the light show to work correctly, each of the LEDs must be controlled individually, meaning that 120 separate control pins are required. This requires an external 120 bit buffer constructed from 74LS273 octal buffer chips. Each chip has 8 flip-flops, meaning that 15 chips are required to

implement the entire buffer. When in operation, the AVR processor places the first 8 control bits on the data lines, then toggles the Clock bit of the first buffer chip to latch the data into the flip-flops. It then places the next 8 bits on the data lines and toggles the Clock bit of the next chip. This process continues until all 120 bits have been latched into the buffers.

Problem Definition

The constant current circuit is effective at maintaining a constant current, but the voltage is not stepped down in any way. The 16 Volts is currently being applied directly across the line. In the case of the red line, the LED's only drop approximately 7.5V, so approximately 8.5 V are being dropped across the transistors. This means more than 50% of the power is being consumed or lost in the transistors. The lost power is expelled in the form of heat, necessitating the need for large heat sinks on the transistors.

In order to remedy this issue, we were tasked to develop a power supply that is more efficient, and does not have the extreme heat losses that the current power supplies have. This power supply needs to have a constant current for the LED lines in the range of 270 – 300 mA, and have at least three different output voltages to account for the three different LED colors. This power supply, or at least multiples of the power supply, needs to be able to power 120 LED lines and be controlled by the Atmel AVR processor.

Project Plan

Schedule

Spring Semester

- 2013-10-09
 - Testing and analysis of final design complete
- 2013-10-17
 - Present chosen design and test results to customer
- 2013-10-19
 - Begin final production
- Course specific dates will be added as they are posted for the following milestones
 - Design review
 - Expo
 - Final report

Concepts Considered

Voltage Control

As previously mentioned, the most pressing issue with the current supplies is the large voltage drop across the transistors. This drop causes the loss in efficiency as well as the heat dissipation.

The obvious solution to this problem was to reduce the input voltage to the minimum voltage required for each diode string. For the red LEDs, this was about 7.5 V and for the green and blue LEDs it was about 10.5 V. To efficiently reduce this input voltage, the best option was to use a switching mechanism. For this application, a buck converter was chosen to control the input voltage. Shown in Figure 3, the buck converter works by using a switching transistor that has a switching frequency between 100 kHz and 1 MHz.

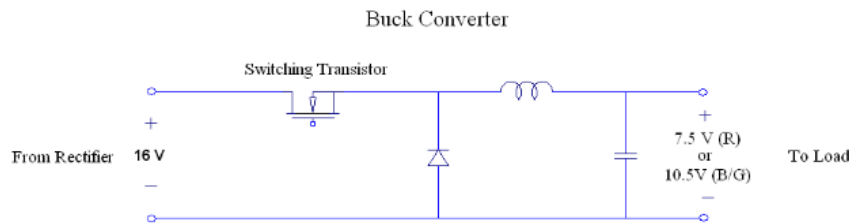


Figure 3. Buck Converter Implementation

When the switch is closed, the 16VDC input source is connected to the load, the diode reverse biased, and the output capacitor begins to charge. When the switch is open, the source is disconnected from the load. However, the current still flows because the inductor does not allow for instantaneous changes in current. Instead, current decreases as does the output voltage as the capacitor discharges. By modifying the percentage of the period associated with the switching frequency in which the switch is closed, the output voltage can be decreased to anywhere between 16VDC and 0 V.

Of course to properly implement a buck converter in the design of the power supplies, a buck converter chip that could achieve high enough switching frequencies while also delivering the required current is needed. Several chips were considered, however the chip chosen was the TPS5430^[1]. This chip had an adequate switching frequency of 500kHz, can tolerate input voltages between 5.5V and 36 V, and can produce up to 3 A of output current. Since 12A of output current is required for each color LED, 4 of these chips would be needed for each color.

The use of this converter will increase efficiency by approximately 34% for the blue and green LEDs and 53% for the red LEDs. The downside to this efficiency increase is the cost of the buck converter chips. Luckily the TPS5430^[1] chips chosen are relatively cheap at are \$2.25 each.

One final thing to take into consideration when using the chosen TPS5430 is that it has a pin, called V_{sense} . The chip will adjust the output voltage, PH, to ensure that the V_{sense} voltage is always 1.22V. The regulation of the V_{sense} voltage will be discussed later in the report. The simplified schematic of the TPS5430^[1] buck converter chip is shown in Figure 4.

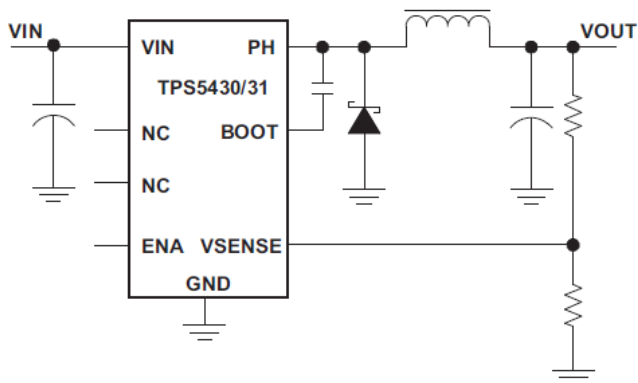


Figure 4. TPS5430 Buck Converter

Switching Options

With the addition of the buck converter to the power supply circuit, the voltage problem was all but solved. However, the current through each string of LEDs also needed to be regulated between 270 mA and 300 mA. Additionally, total current delivered to the load needed to be kept constant when a different number of diode strings were on due to switching. To solve this problem, three possible design solutions were explored. All solutions include the use of the previously mentioned buck converter chip, with different possibilities for the switching and load circuits. Below are the concepts for these three possibilities.

Option #1: Stay the same

The switching is controlled by the same constant current circuits already in use. The buck converter would set the input voltage to 10.5V for blue and green LEDs and 7.5V for red. This alone would reduce the power output and heat dissipation by 34.34% for blue and green and 53.13% for red. Figure 5 below shows the switching circuit currently in place.

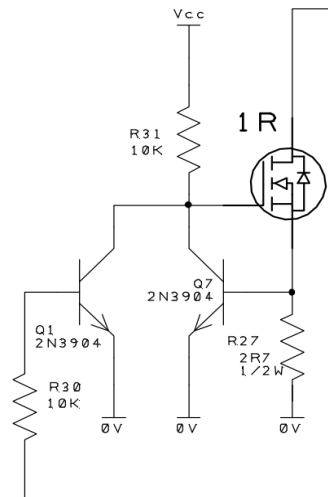


Figure 5. Pre-existing switching circuit

This design is proven to work, and would reduce the cost of production since it is already in place. The downside is that it requires three transistors per line..

Option #2: Path Switching

The path switching solution gives an alternate line for each LED string each with a transistor switch. When the transistor on the LED line is switched on, current flows through the LEDs and lights them. When the LED line is switched off, the alternate path is switched on, allowing the current to flow through an equivalent resistor. This circuit is shown in Figure 6 below.

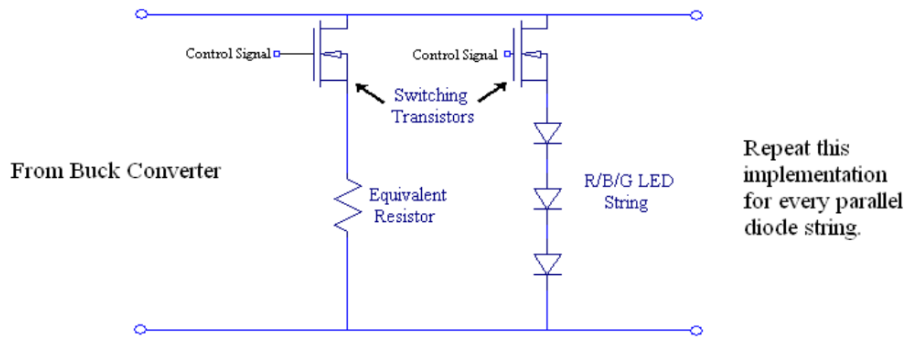


Figure 6. Path Switching Circuit

This solution uses fewer components than Option #1, but energy loss is increased on the alternate resistive path.

Repeat this implementation for every parallel diode string.

Option #3: Current Regulator

The addition of a current regulator chip to the output of the buck converter would reduce the energy loss seen in Option #2. A current “dimmer” chip was selected that would vary the output based on input controls. The current sent to the load is adjusted based on the number of LED strings that are switched on at a time. While the addition of a chip adds a layer of complexity to control and ups the cost, this solution would further reduce unnecessary energy consumption. Figure 7 shows the current regulator circuit.

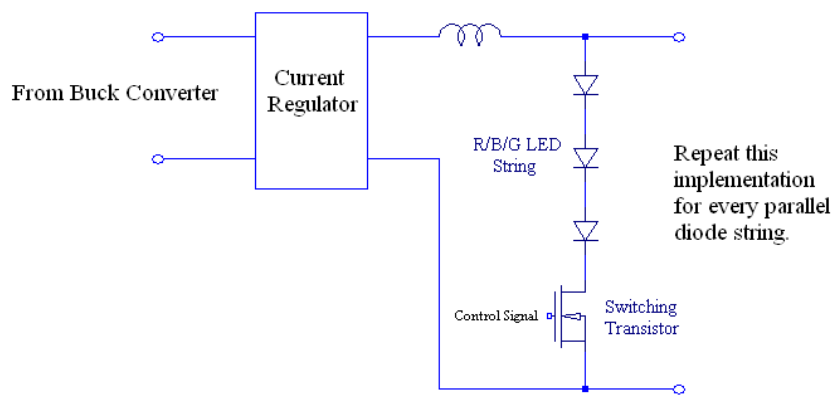


Figure 7. Current Regulation Chip

At the time, Option #3 was chosen as the best solution to the switching and current regulation issue.

V_{sense} Regulation

After settling on a current regulation mechanism the best way to ensure constant current through each LED string, the next step was to find a way to regulate the V_{sense} and output voltages, in order to vary the voltage for each LED type. Three options were found to solve this problem, all of which are discussed below

Option #1: Potentiometer

This option used a voltage divider to keep the V_{sense} at the required 1.22V. By placing a set resistor between the output and V_{sense} while using a potentiometer between V_{sense} and ground, the output voltage could be controlled by adjusting the potentiometer. This option (shown in Figure 8) introduced an element of user error, as it would require eight hand-adjustable knobs to the circuit and each output node would have to be adjusted based on the expected load of the LEDs string attached.

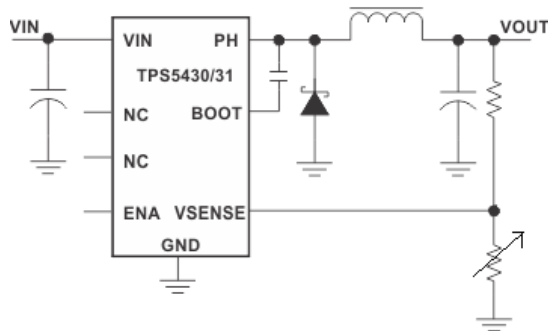


Figure 8. TPS5430 with Potentiometer

After presenting this option to the customer, it was decided that this particular implementation of the TPS5430 would be too cumbersome for potential student users.

Option #2: Switching Mechanism

This option involved switching between four separate voltage dividers. The chosen load resistor would be connected to four different transistors. Depending on the load (either red LEDs, blue LEDs, green LEDs, or the test board), a different output voltage would be required and a different transistor would be turned on. Each transistor would activate a different voltage divider that would set V_{sense} to the required 1.22 V while keeping the output voltage at the required level. A simplified circuit diagram of this option is shown in Figure 9.

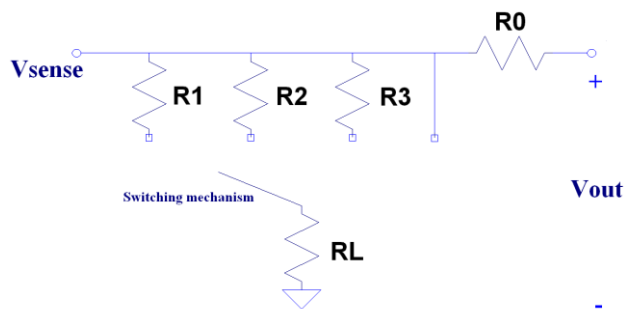


Figure 9. Switching Mechanism

This option introduces a bit more complexity to the circuit as it would require more transistors. On top of costing more to produce, this would also require attached a switch to each supply that set the voltage to the correct level depending on the LED color. In the end, this option was also disregarded since it was not self-adjusting, and would be difficult to implement.

Option #3: Using the Voltage Drop Across the Diode Strings to Set V_{sense}

The third, and most efficient option was to connect the output voltage and the V_{sense} pin using the diode string and the control transistor. The implementation is shown below in Figure 10.

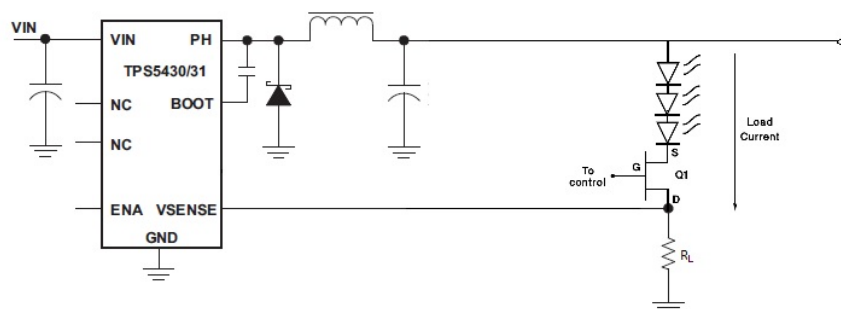


Figure 10. Connecting V_{out} to V_{sense} Using the Diode String

This circuit uses the voltage drop across the diode strings to set the voltage at V_{sense} . The output voltage in this design would be set to approximately 1.22V above the total voltage drop of the three series diodes. That way, when the control signal turned the LEDs on, they would drop either 7.5 V or 10.5 V (depending on the color) and set the V_{sense} pin to the required value. To ensure that the current through these diodes is about 300 mA, a load resistance of about 4 ohms (1.22 V divided by 300 mA) can be inserted at the V_{sense} node as shown in Figure 10. This implementation solves both the V_{sense} regulation, and the current regulation problem in one step.

Concept Selection

Taking all of the options for the switching as well as the V_{sense} regulation into consideration, the correct choice was fairly obvious. As previously mentioned, the implementation displayed in Figure 10 solves the issue of V_{sense} regulation as well as current regulation. Thus, it was the design chosen for the power supply. By attaching a load resistor of approximately 4 ohms from the V_{sense} pin to ground and adjusting the input voltage to be 1.22 V larger than the total voltage dropped by series diodes, a current of roughly 300 mA can be obtained.

In addition to solving the issues involving the V_{sense} pin and the current regulation, this circuit also eliminates the need for the constant current control circuit shown in Figure 2. This reduces the number of transistors needed for each diode string by two. The downside of this option is that the some power will still need to be dissipated across the load resistor, and as a result there will be some excess heat. However, the amount of power loss is still reduced significantly from the original design (2.55 W to 0.36 W).

A small issue does arise when the two transistors in the constant current circuit in Figure 2 are removed. In the current system the control lines are active low, meaning that turning one of the

control transistors off will result in current flowing through the diodes. However, in Figure 10 the control lines would need to be active high, meaning that turning the control transistor on would result in current flowing through the diode strings. This is a relatively small issue, as it can be fixed by simply placing inverters on the control lines or inverting the signals in the control code. It is however worth mentioning since it is a crucial modification that would be necessary for the light show to work properly.

Overall this option was clearly the best one, as it solved two difficult problems at the expense of a small amount of power loss. The reduction of transistors used is also beneficial, even if it requires inverting the control signals. It should be noted that current regulation problem is not completely solved by this implementation. The design chosen works well for one diode string, but implementing this design for every string would require one buck converter chip for every parallel string. This option is not unrealistic since the chips are relatively cheap, but there are other options out there that don't require the use of a chip for every diode string. It is possible to only have one diode string per supply regulated in the manner shown in Figure 10 with the rest using the constant current circuit shown in Figure 2. This design would cut down on the number of chips used, but would not regulate the current as efficiently as the circuit in Figure 10. Thus, the final design will have one chip per diode string.

Appendix – Useful Links

- 1.) Datasheet - TPS5430 Step Down Converter with Vsense
<http://www.ti.com/product/tps5430>
- 2.) Datasheet – Buck Converter Calculations
<http://www.ti.com/lit/an/slva477a/slva477a.pdf>
- 3.) Schematic – Circuit in currently used power board
http://seniordesign.engr.uidaho.edu/2012-2013/power_lights/documents/oldschem.pdf
- 4.) Customer Statement
http://seniordesign.engr.uidaho.edu/2012-2013/power_lights/documents/towerlights.pdf
- 5.) Project Webpage
http://seniordesign.engr.uidaho.edu/2012-2013/power_lights/index.html