Lab 1
Linear Regulated Power Supply

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Abstract

Power supplies that provide DC voltages are critical to the operation of most electronic systems. The task was to design a prototype of a linear regulated power supply that would output 19 V within ±500 mV over a range of 100 mA to 1 A. Computer simulation and breadboard testing were done to simulate the operation of the power supply before creating the actual device. The power supply output 18.991 V at 100 mA and 18.876 V at 1 A.

Introduction

Millennium Engineering provides power for their circuits and systems designed for customers. Regulated power can be provided to circuits by a battery, a simple linear power supply, or a complex switching power supply. The task was to properly design, implement, and test a regulated power supply and provide documentation for all work.

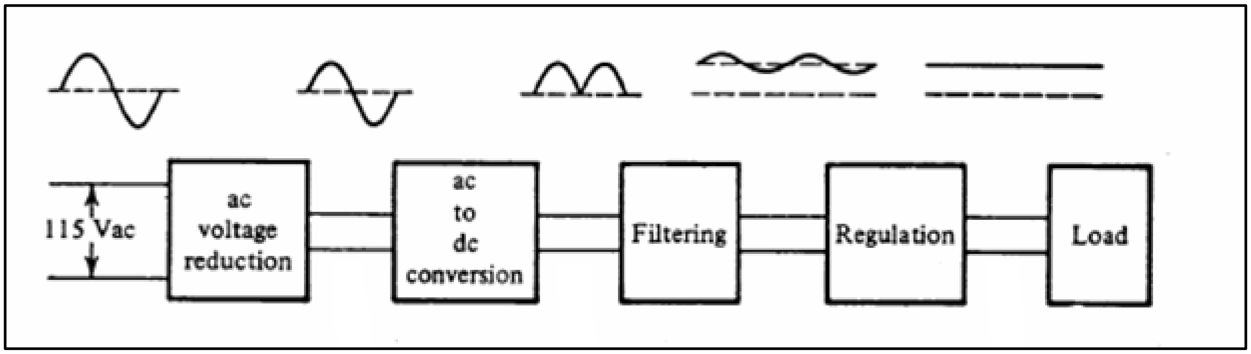


Figure 1: DC Power Supply Block Diagram [1]

The original AC signal comes from a wall outlet. The AC voltage reduction was performed by a low-voltage, center tap transformer.

The Rectron Semiconductor RS402L Single-Phase Glass Passivated Silicon Bridge Rectifier was used to perform the AC to DC conversion.

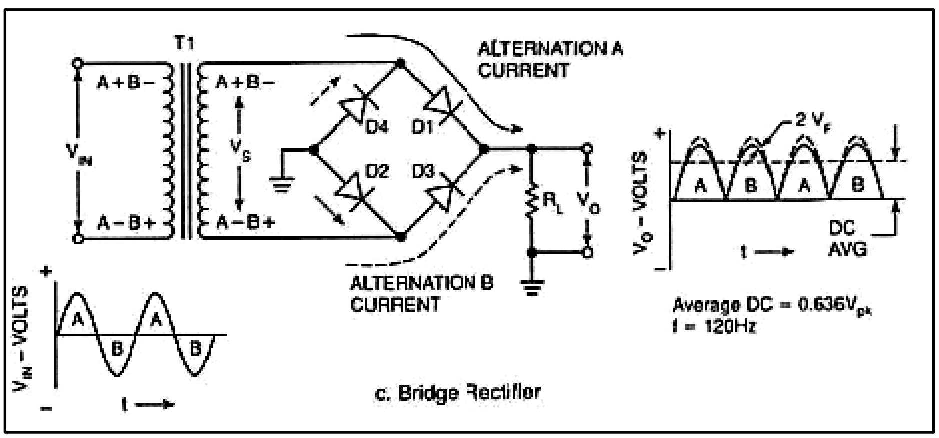


Figure 2: Transformer Output into Bridge Rectifier with Load and Output Waveform [1]

To reduce the voltage ripple the signal was passed through a capacitive filter. Capacitors were used rather than inductors because they are smaller and weight and cost less.

Ideally, voltage regulation provides a constant output voltage regardless of the required output current. The National Semiconductor LM723 Voltage Regulator was used for this purpose. The regulator keeps the output voltage steady by using an active component in series with the load which regulates the current flow to the load.

The regulator requires resistors at the output to set the feedback for the op-amp within the regulator. The resistors were selected to give the desired output voltage of 19 V.

The LM723 can only supply output currents up to 150 mA so an external transistor had to be used. The transistor used was the Motorola TIP-31 Power Transistor. This allowed the output current to achieve the specified design range of 100 mA to 1 A.

To avoid overheating of the TIP-31 the AAVID Thermalloy TO-220 Heat Sink was used.

Methodology

The design of the linear regulated power supply follows the block diagram in Figure 1. The left side of the diagram is where the process starts. A voltage of approximately 120 V_{rms} (169 V_{pk}) is taken from the wall outlet. The AC voltage reduction block is the low-voltage center-tap transformer box. This transformer has the ability to use its full output or half of it using the center-tap. Since the assigned test output voltage was 19 V, the output voltage of the transformer needed to be larger than the load output voltage. Using a Fluke multimeter, the transformer's center-tap and full output voltage were 19.31 V_{pk} (13.66 V_{rms}) and 38.7 V_{pk} (27.35 V_{rms}). Using the following equation, the peak voltage can be converted to root mean square voltage.

$$V_{pk} = \sqrt{2}V_{rms} \qquad (1)$$

The measured result allowed for the transformer turns ratio to be calculated. This was needed for the Cadence PSpice simulation. Using equation 2 and Figure 3, the turns ratio was calculated to be 0.2289.

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \qquad (2)$$

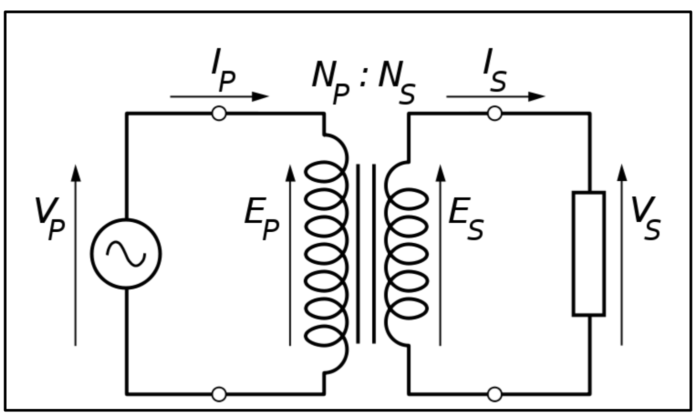


Figure 3: Diagram of Transformer and Corresponding Parameters [2]

Where V_P and V_S are the primary and secondary voltages, respectively, and N_p and N_S are the number of turns in the primary and secondary coils, respectively. The transformer produced a sinusoid on the Agilent 54622A oscilloscope like in Figure 1.

The output of the transformer goes to an RS402L bridge rectifier to convert from AC to DC. The rectifier should produce a constantly non-negative waveform like in Figure 1. From Figure 2, this rectifier consists of four diodes.

The voltage output of the rectifier was 1.4 V lower than the input. A power resistor of 1 Ω was placed in series with the rectifier. This resistor limited the secondary current of the transformer which can affect the primary current due to the turns ratio relationship. The transformer can only handle 0.5 A before the fuse in the transformer blows. A resistance of 0.5 Ω was determined to be sufficient to limit the secondary current. A filter was required to eliminate the lower voltage component of the signal. The waveform after the "Filtering" block in Figure 1, shows how the waveform would ideally look. Figure 4 shows the different voltage parameters necessary for describing the filter output.

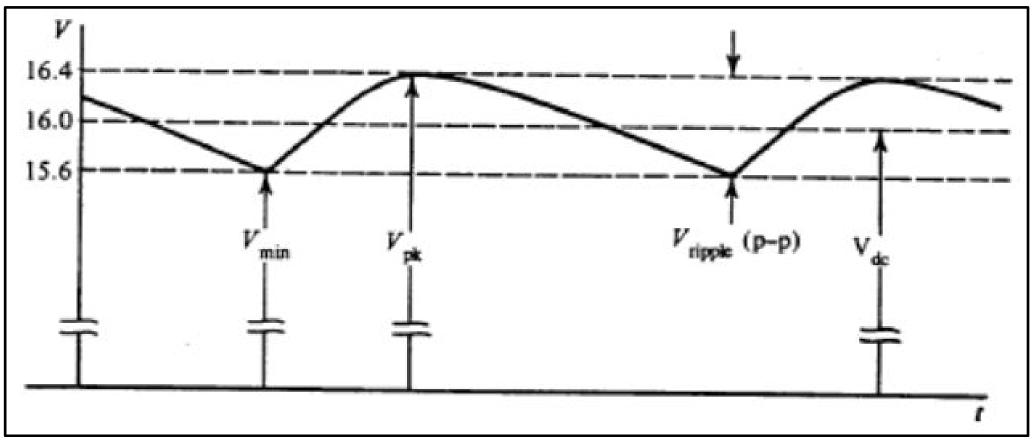
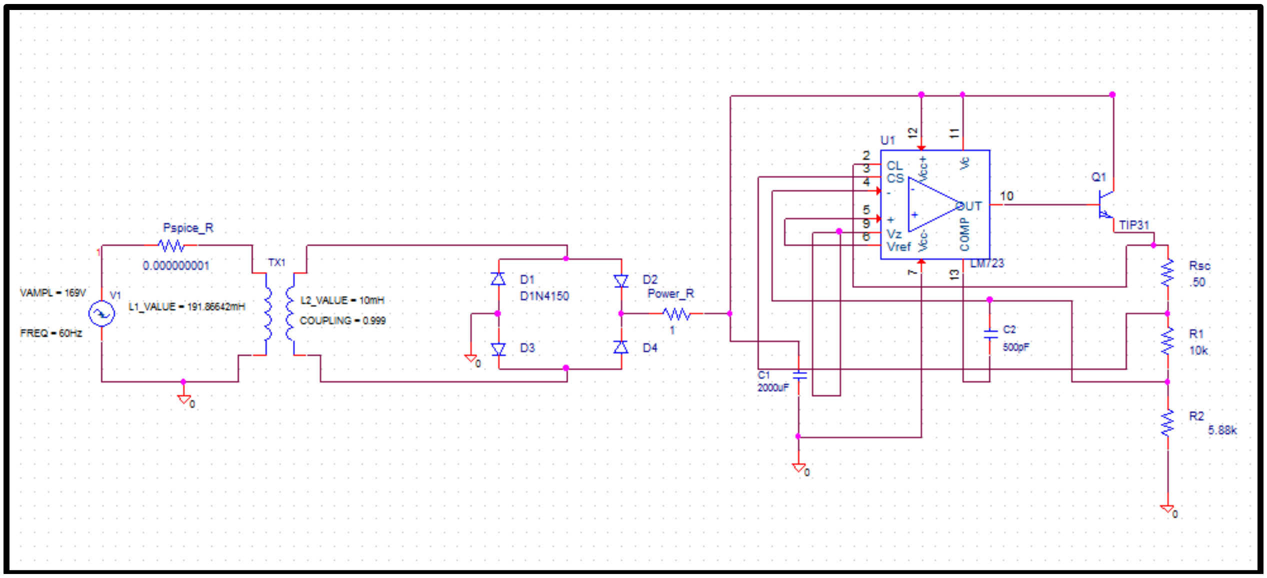


Figure 4: Output of Filter with Corresponding Voltage Parameters[1]

The LM723 regulator was used after the filter and the layout for pin assignments can be seen in the PSpice schematic in Schematic 1.

The circuit design includes a TIP-31 transistor that can boost the current since the finished power supply has to be able to handle at least 1 A. To construct this circuit, a Cadence PSpice design in Schematic 1 was made using the same components specified. Values were calculated for resistances and for the filter.



Schematic 1: Cadence PSpice Schematic of Linear Regulated Power Supply

The design was tested on a breadboard. 2000 µF capacitors were not available so two 1000 µF capacitors were used in parallel. The Agilent oscilloscope, Fluke multimeter, and Power Resistor Decade Box were used in the breadboard testing phase. The breadboard design produced the expected results. It was decided during the breadboard testing phase that a potentiometer would be needed to obtain the desired output. The calculations called for a 5.88 kΩ resistor, but only6 kΩ resistors were available. Series resistors were considered but a potentiometer provided a simple solution.

The design was then implemented on the copper plated proto-board The proto-board was smaller than the breadboard so the TIP-31was placed far away from other components because of the amount of heat it generated. The TIP-31 required a heat sink to keep the transistor from overheating. The maximum heat sink thermal resistance allowed was determined to be 2.138 ºC/W using the equation below.

$$\frac{T_j - T_a}{I_{max} * V_{test}} = \theta_{jc} + \theta_{sa} \qquad (3)$$

$$\frac{150°C - 25°C}{1.25A * 19V} = 3.125\ \frac{°C}{W} + \theta_{sa}$$

Where T_j and T_a are the junction and ambient temperatures, respectively. The junction temperature is determined as the maximum temperature specified on the data sheet for the TIP-31. I_{max} and V_{test} are determined by how much current the circuit should handle at the specified test voltage. θ_{jc} and θ_{sa} are the junction to case and sink to ambient thermal resistances, respectively. The junction to case thermal resistance is specified on the data sheet.

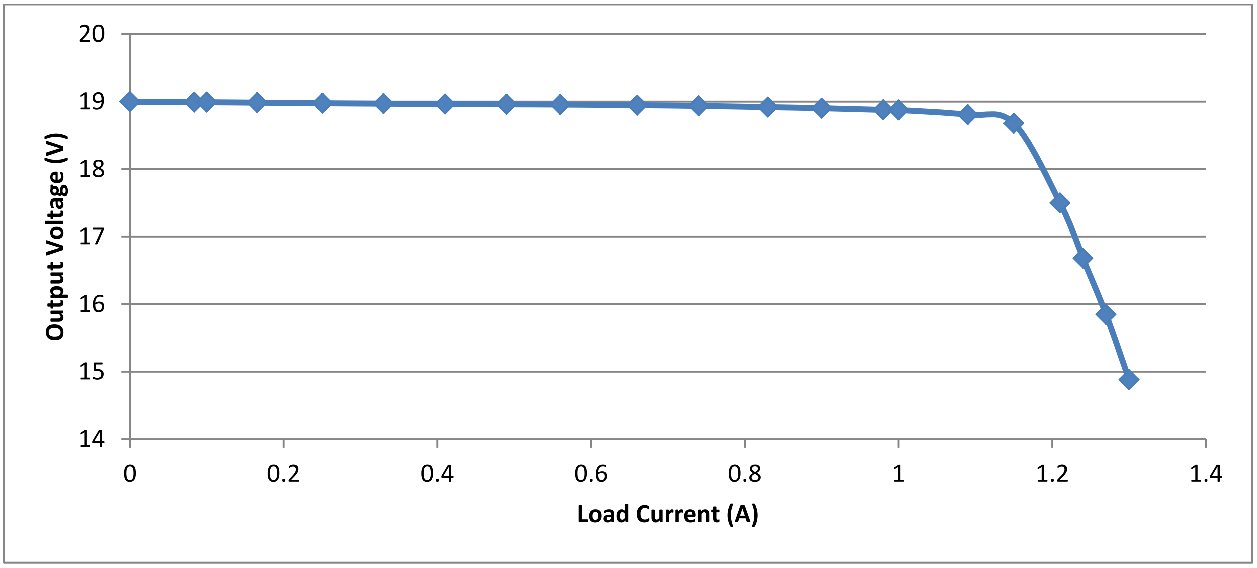
The main proto-board design issue was utilization of nodes. The board has two common nodes throughout the board. There are also nodes for each row. The common nodes were used for ground and for the node that connects pins 11 and 12 to the power resistor at the rectifier output and to the collector of the transistor. Special holes had to be drilled because the rectifier pins were too large. The drilling was done carefully so as to not rip the copper plating off. If components could not be directly connected via shared nodes on the proto-board, wires were used to connect nodes.

Results

The linear regulated power supply produced a sustained V_{out} of 19 V. I_{out} ranged from 100 mA to 1 A and V_{out} randged from 18.991 V to 18.876 V. The regulated over-current protection successfully limited the current to 1.25 A. All of the design specifications were met. Table 1 shows the measured values for V_{out}, I_{out}, and R_{load}. Graph 1 plots the data.

Table 1 - Output measurements under No-Load to Max-Load

Output Voltage (V)	Output Current (A)	Output Resistance (Ω)
18.998	0	Open load
18.992	0.0838	222
18.991	0.1	189
18.985	0.1658	109.1
18.976	0.2507	70
18.97	0.33	59.8
18.963	0.41	46.6
18.96	0.49	38.6
18.957	0.56	33.8
18.948	0.66	28.6
18.937	0.74	25.6
18.919	0.83	22.6
18.903	0.9	20.8
18.878	0.98	19.3
18.876	1	18.6
18.807	1.09	16.8
18.68	1.15	15.7
17.5	1.21	13.9
16.68	1.24	13.5
15.85	1.27	11.9
14.88	1.3	10.9



Graph 1 - Output Voltage vs. Load Current under No-Load to Max-Load

V_{out} drops less than 100 mV until I_{out} is 0.98 A. When I_{out} is 1 A, V_{out} is 18.878 V which is well within the ±500 mV acceptable range. The current limiting effect can be seen when I_{out} is equal to about 1.15 A as the voltage drops from 18.68 V to 17.5 V. The voltage continues to drop as the current increases. The final measurement taken was I_{out} equal to 1.3 A with V_{out} equal to 14.88 V. This means that over a current range of 150 mA the output voltage dropped 4 V which is indictitive of the current limiting capabilities designed around 1.25 A. The proper R_{sense} value was calculated from Equation 4

$$I_{Limit} = 1.25\ A = \frac{V_{sense}}{R_{Sense}} = \frac{0.7}{R_{Sense}} \qquad (4)$$

The sense voltage, V_{sense}, was determined by the voltage drop required to turn on the current limiter transistor inside of the LM723, and the limiting current was given the value 1.25 A. The value determined for R_{sense} was 0.56 Ω however two 1 Ω power resistors were used in parallel to form a 0.5 Ω R_{sense} value in the implementation.

The output voltage ripple was examined when the load current was 100 mA and 1.002 A. Figure 5 and Figure 6 show the results.

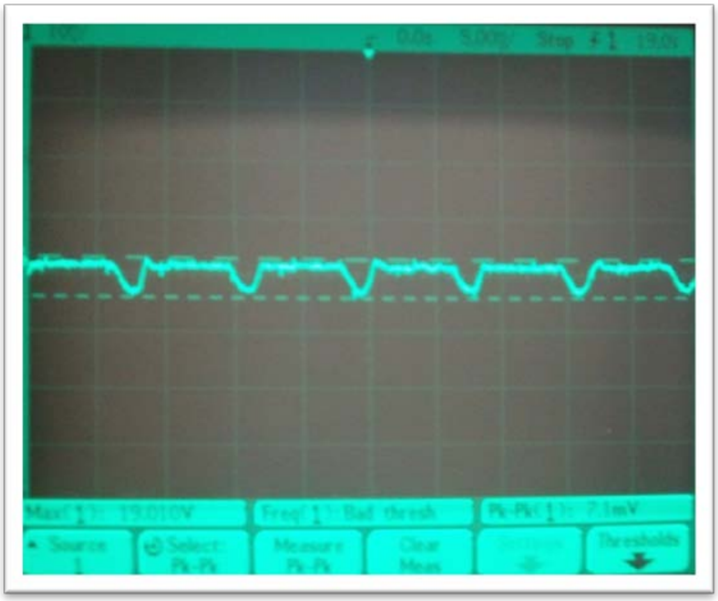


Figure 5 - Output Voltage Ripple - I_{Load} = 100 mA; V_{pp} = 7.1 mV; 5 ms/div; 10 mV/div

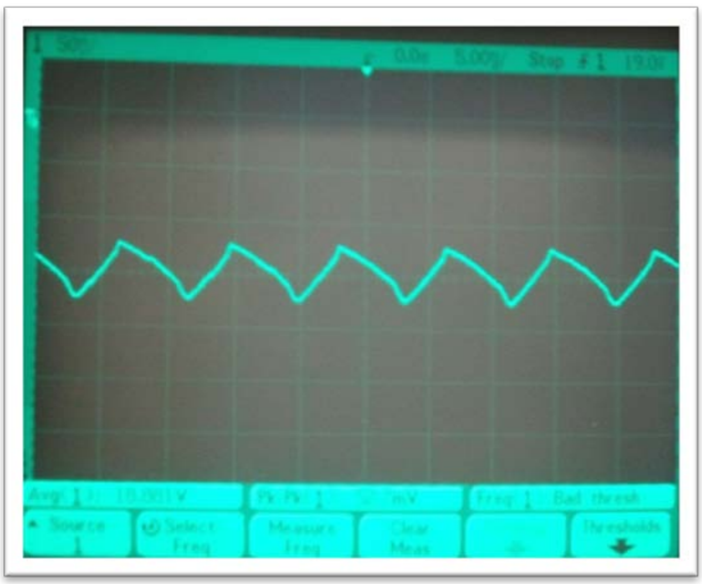


Figure 6 - Output Voltage Ripple - I_{Load} = 1.002 A; V_{pp} = 52.7 mV; 5 ms/div; 50 mV/div

The voltage ripple can be characterized as looking like an ideal band-pass filter. There is a fast rising front edge that evens out towards a relatively flat region which is then followed by a sharp falling edge. The dominant frequency was measured using horizontal cursors over one cycle of the waveform. The dominant frequency was measured to be 120 Hz. This makes sense because full wave rectification was used causing the 60 Hz outlet supply to double because each negative slope on the sinusoid was positively polarized causing twice as many peaks. Examining Figure 6, it is interesting to note that at lower valued loads the output voltage ripple changed forms appearing without the relatively flat region. The wave form resembled a triangular wave when the load current was 1.002 A.

The thermal junction temperature of the TIP-31 transistor was approximated by measuring the collector voltage as well as the output voltage, and the temperature of the case when the output current was 1 A which is the maximum supported current. The power dissipated, P_D, by the TIP-31 was calculated by finding the potential difference across the TIP-31 and multiplying it by 1 A to obtain an approximated P_D of 9.45 W. The thermal equation to calculate the junction temperature was set up by using the following analogies: Power – Current; Thermal Resistance – Resistance; Temperature – Voltage. Using these relationships Ohm's law and circuit theory could be used to calculate thermal quantities.

$$T_j = T_c + \theta_{jc} * P_D \qquad (5)$$

The case temperature, T_c, was measured with the infrared temperature meter to be 60.7 °C, and the thermal resistance between the junction and the case, θ_{jc}, was obtained from the TIP-31 manual to be 3.125 °C/W. The junction temperature, T_j, was calculated to be 90.23 °C. This is nearly 60 °C lower than the maximum junction temperature specified by the manual which has a maximum temperature of 150 °C.

Conclusions

The load regulation K, which is defined as the change in output voltage from minimum to maximum with all other factors held constant, was calculated with Equation 6.

$$K = \frac{V_{rl(\max)} - V_{rl(\min)}}{V_{rl(\min)}} x\ 100 \qquad (6)$$

The values for $V_{rl(\max)}$ and $V_{rl(\min)}$, which are the minimum and maximum voltages at 100 mA and 1 A, were 18.876 and 18.991, respectively. The load regulation K was determined to be 0.6092.

The internal resistance for our device was calculated by solving a voltage divider equation.

$$V_L = \frac{R_L}{R_L + R_T} * V_T \qquad (7)$$

There are two unknowns, V_T and R_T, and two equations which can be formed using two sets of data from Table 1 which give the V_L and R_L values. The calculated values are V_T equal to 18.931 V and the internal resistance R_T equal to 0.0545 Ω.

The power efficiency, ŋ, for the device was calculated at maximum supported current load of 1 A using the following equation along with Table 1 and the Kill-A-Watt.

$$\eta = \frac{P_L}{P_S} = \frac{18.876}{39.1} = 0.483 \qquad (8)$$

The power efficiency is almost 50% which is to be expected with a linear regulated power supply. A more efficient supply such as a switching power supply would achieve a higher efficiency because the power transistor will not always be in active mode dissipating more heat than it would in saturation or cutoff mode.

Recommendations

A linear regulated voltage power supply is typically inefficient which can be seen from equation 8. This is due to heat being dissipated from the transistor. A switching power supply would be more efficient. The current limiting properties of the circuit cause the current to drop before 1.25 A. This is due to the power resistors at the output of the LM723 regulator. The total resistance there is 0.5 Ω, but the PSpice simulation called for 0.56Ω. Another path to take is to add a capacitor in parallel with the load. It would reduce the output voltage ripple.

References

[1] Prescott, Glenn. “Power Supplies and Linear Regulators.” cresis.ku.edu/~callen. 15 September 2011. <https://www.cresis.ku.edu/~callen/501/LinearRegulators.pdf>.

[2] Wikimedia Commons. Transformer Under Load. 18 April 2007. Commons.Wikimedia.org. 15 September 2011. <http://commons.wikimedia.org/wiki/File:Transformer_under_load.svg>.