MATERIALS

1. Problem Statement (4 situations)
2. Sample Solution
3. Notes for the Instructor

Computing Requirements: Scientific Calculator (optional)

The Electronic Power Supply

INTERDISCIPLINARY LIVELY APPLICATION PROJECT
TITLE: THE ELECTRONIC POWER SUPPLY
AUTHORS: THEODORE INGRAM
         SHAHRYAR DARAYAN
         DELLA BELL
         ANDREW MATTHEW
         CARRINGTON STEWART
         MICHAEL AGINA
         RASOUL SANEIFARD

ELECTRONICS ENGINEERING TECHNOLOGY AND MATHEMATICS DEPARTMENT,
TEXAS SOUTHERN UNIVERSITY, HOUSTON, TEXAS

EDITORS: DAVID C. ARNEY
          KELLEY B. MOHRAMANN

MATHEMATICS CLASSIFICATION: ALGEBRA AND PRECALCULUS
DISCIPLINARY CLASSIFICATION: ELECTRONICS ENGINEERING TECHNOLOGY
PREREQUISITE SKILLS:
1. FORMULATE AND SOLVE ALGEBRAIC EQUATIONS
2. UNDERSTAND BEHAVIOR AND CHARACTERISTICS OF ELECTRONIC
   COMPONENTS
3. INTERPRET DIODE DATA SHEETS
4. CIRCUIT ANALYSIS SOFTWARE

PHYSICAL CONCEPTS EXAMINED:
1. TRANSFORMER ACTION
2. SEMI-CONDUCTOR MATERIALS
3. RESISTANCE
4. CAPACITANCE

NSF INITIATIVE:
MATHEMATICS SCIENCES AND THEIR APPLICATIONS THROUGHOUT THE CURRICULUM
(CCD-MATH)

INTRODUCTION

Electronic circuits need energy to work. In most cases, this energy is provided by a circuit called the power supply. The power supply is a key part of any electronic system, since it energizes the other circuits. A power supply failure will affect all of the other circuits. The power supply changes the available electric energy (usually *alternating current-ac*) to the form required by various circuits within the electronic system (usually *direct current-dc*). A power supply converts the ac voltage to a steady dc level. The output signal is filtered to an accurate dc output voltage. This dc voltage is automatically maintained through regulation. The most common electrical power source is that furnished by the local power company, and is 115 volts alternating current at a frequency of 50 or 60 Hertz (cycles per second). Batteries are also electrical power sources.

Power supplies may be built or designed to meet certain requirements. The four blocks of the power supply include: (1) *transformer*, whose purpose is to step-up or step-down the alternating current voltage to levels needed by the boom box, television, computer or other electronic circuits of various electrical equipment or appliances; (2) *rectifier*, which is used to change an AC input into a pulsating DC output; (3) *filter*, which is needed to smooth out the direct current; and (4) *regulator*, which is used to eliminate the decrease in output voltage of a power supply when a load is applied. **Figure 1** shows the six blocks of a dc power supply.
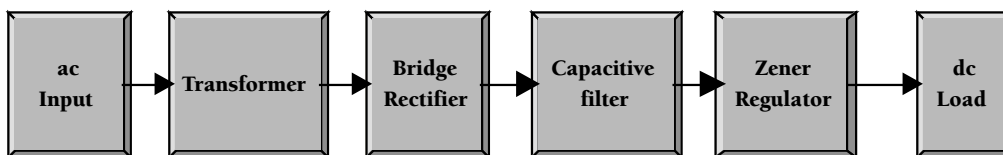

Figure 1.
BLOCK DIAGRAM OF
POWER SUPPLY

Formulas are used in determining voltage regulation, filter capacity, etc. Skills in algebra and other areas of mathematics are useful in utilizing the formulas correctly. While studying the power supply ILAP, you will have the opportunity to reinforce algebraic concepts.

A schematic diagram of the electronic power supply is shown in **Figure 2**. This diagram indicates how the four blocks of Figure 1 are connected to form the power supply. This ILAP is designed to provide experiences in calculating values needed to design an electronic power supply.
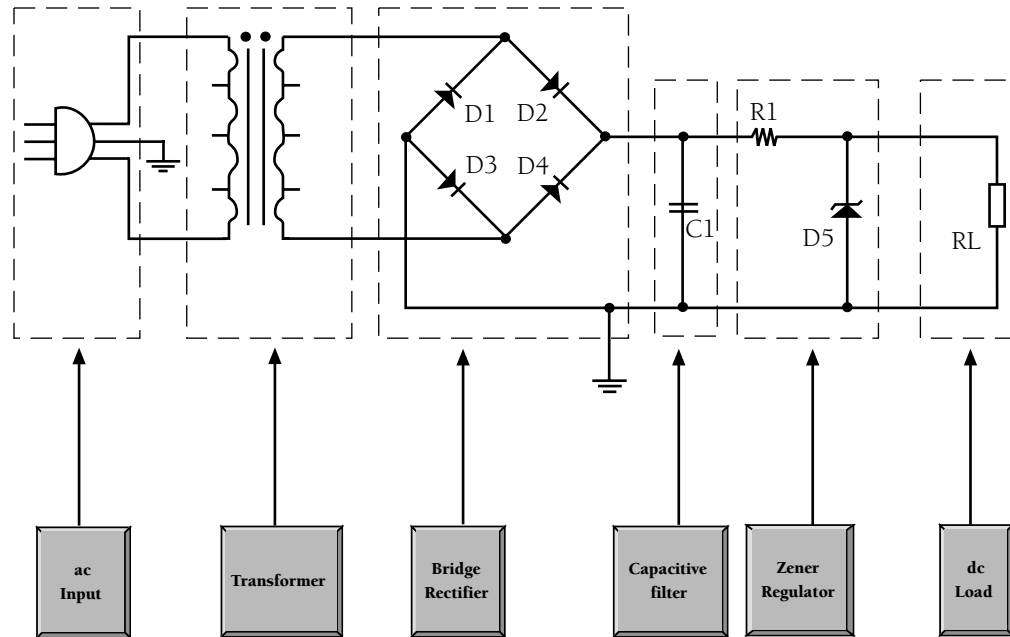
Figure 2.
SCHEMATIC DIAGRAM OF
POWER SUPPLY

PREREQUISITE SKILLS

1. ABILITY TO FORMULATE AND SOLVE ALGEBRAIC EQUATIONS;
2. KNOWLEDGE OF THE BEHAVIOR AND CHARACTERISTICS OF ELEC-
   TRONIC COMPONENTS SUCH AS DIODES, TRANSFORMERS, RESIS-
   TORS, CAPACITORS, AND INDUCTORS;
3. ABILITY TO INTERPRET AND APPLY INFORMATION FROM DIODE
   DATA SHEETS; AND
4. KNOWLEDGE OF WORD-PROCESSING AND CIRCUIT ANALYSIS SOFT-
   WARE SUCH AS PSPICE, ELECTRONIC WORKBENCH, AND
   BREADBOARD.

SITUATION 1: TRANSFORMER

A transformer is included to step the ac line voltage up or down to a desired value. For most electronic equipment a voltage of less than 115 volts is required, and therefore a step-down transformer is needed. The transformer consists of two or more coils (a primary winding and secondary winding) linked together by magnetic flux. A step-down transformer's primary voltage is greater than the secondary voltage. If the primary winding turns exceed the secondary turns, the transformer steps the voltage down.

In the design of the power supply one should be able to determine the secondary voltage mathematically using the following relationship for an ideal transformer:

$$\frac{V_{pri}}{V_{sec}} = \frac{N_{pri}}{N_{sec}} = \frac{I_{sec}}{I_{pri}} \qquad (1)$$

Where
N = number of turns,
V = voltage in volts,
I = current in amps,
pri = indicates primary, and
sec = indicates secondary.

REQUIREMENT 1.1.

Use algebraic rules or calculations to show that Equation (1) may be rearranged as

$$\frac{N_{sec}}{V_{sec}}$$

REQUIREMENT 1.2.

Also use algebraic rules or calculations to show that Equation (1) may be rewritten as

$$\frac{N_{sec}}{I_{pri}}$$

REQUIREMENT 1.3.

The concept of turns per volt will be used in modifying the secondary voltage for the design of an electronic power supply. Determine how many turns will be required for a transformer voltage of 14 volts when the present secondary is rated at 6.3 volts and contains 20 turns. How many turns will be required for a new 14V winding?

SITUATION 2: RECTIFIER

The full-wave bridge rectifier (or simply bridge rectifier) uses four semiconductor diodes. The diode is a semiconductor device that exhibits characteristics that lie between those of insulators and conductors. Silicon is the most extensively used semiconductor material for diodes. When the diode is forward-biased (connected to conduct or behave like a conductor) it acts like a closed (on) switch which will permit current to flow. On the other hand, when the diode is reversed-biased (characteristics like an insulator), it acts like an open switch (off). A forward-biased silicon diode acts as a closed switch with a small voltage of 0.7 volt barrier potential. Germanium, another semiconductor material used for diodes, has a barrier potential of 0.3 volt.

The full-wave bridge rectifier is the most commonly used type of rectifier circuit used in dc power supplies. Operation of the bridge requires the forward-bias of two of the diodes. Diodes D_2 and D_3 conduct during the positive half-cycle of the input from the transformer. The remaining two diodes do not conduct. With the negative half-cycle, diodes D_1 and D_4 conduct while D_2 and D_3 do not conduct. This is shown in Figure 2. The bridge, in short, switches both half-cycles at the input (a full wave) through to the output in only one direction. However, by applying a negative voltage across the diode, it will be reverse biased and carries almost no current. If this negative voltage increases to the certain amount (breakdown voltage), the diode would go into breakdown. This voltage is known as the peak inverse voltage (PIV).

REQUIREMENT 2.1.

Determine the output voltage for a bridge rectifier utilizing a transformer with a 110 V_{rms} primary and 18 V_{rms} secondary voltage. In order to convert the V_{rms} (root mean square voltage) to the V_{peak} (peak voltage), the following equation will be utilized

$$V_{peak} = 1.414 \times V_{rms} \tag{2}$$

Also, determine the Peak Inverse Voltage (PIV) rating for silicon diodes. The following formula can be used to calculate PIV:

$$PIV = V_{peak}(\text{out}) + 0.7 \tag{3}$$

SITUATION 3: FILTER

The bridge rectifier converts an ac signal to a pulsating dc output. This pulsating dc output is not usable for most electronic circuits. A signal closer to pure direct current is required. Pulsating direct current contains an ac component which is undesirable for the output of a power supply.

The ac component in the power supply is called ripple and must be removed for most circuit applications. A filter circuit is used to remove the ripple and provide an unvarying dc voltage. A common technique used for filtering is the capacitive filter. Capacitors are devices which store energy in the form of a charge and then later deliver that charge to a load.

The capacitor filter provides a nearly smooth (straight line) dc output voltage from the filter. A capacitor connected across a rectifier output quickly charges at the beginning of a cycle and slowly discharges after the positive peak. Variation in the output voltage due to the capacitor charging and discharging is called the ripple voltage. Furthermore, ripple factor (r) can be defined by comparing ripple voltage ($V_{r\ p\text{-}p}$) to the dc value of voltage(V_{dc}). **Figure 3** shows the relationship between ripple and dc voltages.
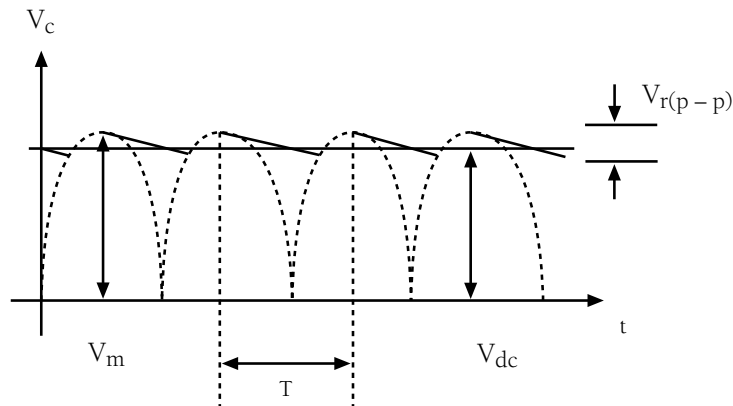

Figure 3.
THE RELATIONSHIP BETWEEN THE FULL-WAVE RECTIFIER VOLTAGE (DOTTED LINE) AND FILTERED OUTPUT VOLTAGE (SOLID LINE).

The following equations can be used to calculate ripple voltage, dc voltage, and ripple factor.

$$V_m = V_{peak}(\sec) - 1.4 \qquad (4)$$

$$V_{dc} = (1 - \frac{1}{2fR_LC})V_m \qquad (5)$$

$$V_{r(p-p)} = (\frac{1}{fR_LC})V_m \qquad (6)$$

$$r = \frac{V_{r(p-p)}}{V_{dc}} \tag{7}$$

Where

V_m = peak rectifier voltage (volts),

V_{dc} = filtered dc output voltage (volts),

$V_{r\ (p-p)}$ = peak-to-peak ripple voltage (volts),

R_L = load resistance (3),

r = ripple factor,

f = frequency (Hz), and

C = Capacitance (Farad).

The amount of ripple across a filter can be further reduced by using an additional RC filter section as shown in **Figure 4**. The purpose of RC section is to pass most of the dc component while attenuating the ripple voltage.
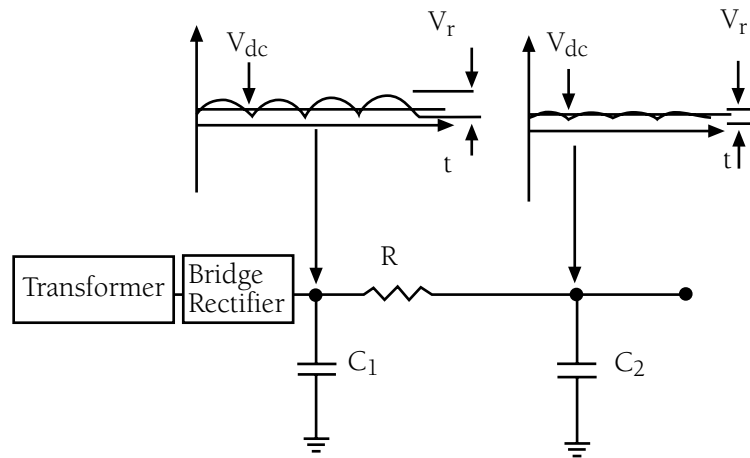

Figure 4.
BRIDGE RECTIFIER AND
FILTER CIRCUIT.

Requirement 3.1.

Determine the ripple factor for a bridge rectifier with a 115 Vrms, 60 Hertz primary transformer. The transformer has a 10:1 ratio. The filter circuit includes a 50µF (microfarads) capacitor with a 2.2 kΩ (2,200-ohms) load resistor.

Requirement 3.2.

Prepare a written technical report on the design of a capacitive filter for a power supply. Your report should include the description and operation of the major blocks, specifications, and components and part numbers to design and fabricate the system. You will be provided a report format.

SITUATION 4: REGULATOR

The dc signal produced with rectifier and filter has a small ac ripple. Any variation in the line voltage supplying the rectifier will increase the variation of the rectifier output voltage. Furthermore, varying the load resistor across the terminal of the power supply will change the voltage level. To overcome all these problems, a Zener diode can be used as shown in Figure 2. The characteristic curve of a Zener diode is shown in **Figure 5**.

The parameters of the Zener diode curve are defined as follows:

V_Z = Zener breakdown voltage (volts),

I_{ZM} = Zener maximum current (Amp), and
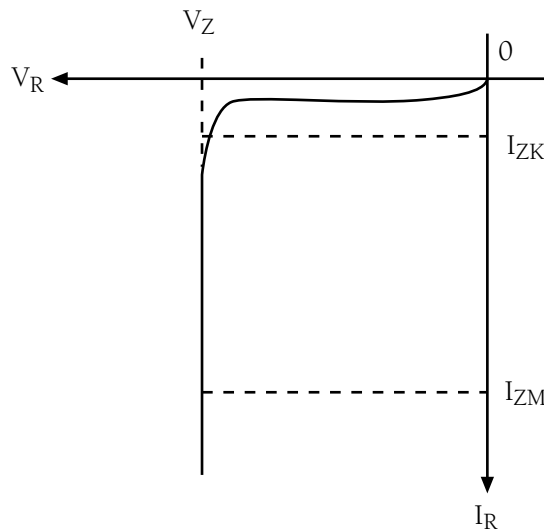
I_{ZK} = Zener knee current (Amp).

Figure 5.
CHARACTERISTIC CURVE
FOR ZENER DIODE

Since the Zener diode and load resistance are in parallel, the voltage across them must be the same.(See Figure 2.) Applying the voltage divider rule, the following relationship is obtained.

$$V_Z = V_L = V_{dc}\left(\frac{R_L}{R_L + R_1}\right) \qquad (8)$$

Solving for minimum load resistance, R_{Lmin} using Equation (8), we have

$$R_{L\min} = \frac{R_1 V_Z}{V_{dc} - V_Z} \qquad (9)$$

The following relationships will allow us to find the maximum load resistance:

$$V_{R_1} = V_{dc} - V_Z \qquad (10)$$

$$I_{R_1} = \frac{V_{R_1}}{R_1} \hspace{3cm} (11)$$

$$R_{L_{max}} = \frac{V_Z}{I_{R_1} - I_{ZM}} \hspace{3cm} (12)$$

REQUIREMENT 4.1.

It is assumed the filtered output voltage, V_{dc}, is fixed, while the load resistance varies. We seek to determine the minimum load resistance that will turn the Zener diode on (maintain regulation). The Zener breakdown voltage V_Z (which remains constant over the range of current values), Zener maximum current I_{ZM}, and Zener knee current I_{zk} are 10V, 15mA, and 1mA respectively. The resistance value for R_1 is assumed to be 1 $k\Omega$ and the dc voltage, V_{dc}, provided by filter stage is equal to 30V.

SOLUTIONS

SOLUTION TO REQUIREMENT 1.1.

Use algebraic rules or calculations to show that:

$$\frac{V_{pri}}{V_{sec}} = \frac{N_{pri}}{N_{sec}} = \frac{I_{sec}}{I_{pri}}$$

may be rearranged as

$$\frac{N_{sec}}{V_{sec}}$$

This expression may be rearranged using properties of proportions.

Consider the proportion of the form

$$\frac{a}{b} = \frac{c}{d}$$

where the denominators are not zero. Then

$$ad = bc,$$

$$\frac{b}{a} = \frac{d}{c},$$

$$\frac{d}{c} = \frac{b}{a},$$

$$\frac{d}{b} = \frac{c}{a},$$

$$\frac{b}{d} = \frac{a}{c}.$$

From Equation (1) above,

$$\frac{V_{pri}}{V_{sec}} = \frac{N_{pri}}{N_{sec}}$$

$$(V_{pri})(N_{sec}) = (N_{pri})(V_{sec})$$

$$N_{sec} = \frac{(N_{pri})(V_{sec})}{V_{pri}}$$

$$\frac{N_{sec}}{V_{sec}} = \frac{(N_{pri})(V_{sec})}{(V_{pri})(V_{sec})}$$

Therefore

$$\frac{N_{\text{sec}}}{V_{\text{sec}}} = \frac{N_{pri}}{V_{pri}}$$

or

$$\frac{N_{pri}}{V_{pri}} = \frac{N_{\text{sec}}}{V_{\text{sec}}}$$

SOLUTION TO REQUIREMENT 1.2.

Use Algebraic rules or calculations to show that the relationship:

$$\frac{V_{pri}}{V_{\text{sec}}} = \frac{N_{pri}}{N_{\text{sec}}} = \frac{I_{\text{sec}}}{I_{pri}}$$

may be rewritten as

$$\frac{N_{\text{sec}}}{I_{pri}}$$

Using the relationship above and properties of proportions and also properties of equalities,

$$\frac{N_{pri}}{N_{\text{sec}}} = \frac{I_{\text{sec}}}{I_{pri}}$$

$$(N_{pri})(I_{pri}) = (I_{\text{sec}})(N_{\text{sec}})$$

$$\frac{(N_{pri})(I_{pri})}{I_{pri}} = \frac{(I_{\text{sec}})(N_{\text{sec}})}{I_{pri}}$$

$$\frac{(N_{pri})(I_{pri})}{I_{pri}} = \frac{(I_{\text{sec}})(N_{\text{sec}})}{I_{pri}}$$

$$N_{pri} = \frac{(I_{\text{sec}})(N_{\text{sec}})}{I_{pri}}$$

$$\frac{N_{pri}}{I_{\text{sec}}} = \frac{(I_{\text{sec}})(N_{\text{sec}})}{(I_{pri})(I_{\text{sec}})}$$

$$\frac{N_{pri}}{I_{\text{sec}}} = \frac{N_{\text{sec}}}{I_{pri}}$$

SOLUTION TO REQUIREMENT 1.3.

$$\frac{N_{pri}}{V_{pri}} = \frac{N_{\text{sec}}}{V_{\text{sec}}}$$

$$\frac{N_{pri}}{V_{pri}} = \frac{20}{6.3} = 3.175 \quad \text{turns per volt}$$

The transformer has a 3.175 turns-per-volt ratio. Since a 14 V secondary is required

$$N = (\text{new secondary})$$

$$= 3.175 \text{ turns per volt} \times 14V$$

$$= 44.5 \text{ turns or 45 turns}$$

Answer: a 14 volt winding needs 45 turns

SOLUTION TO REQUIREMENT 2.1.

Since we have a full-wave bridge rectifier, the peak output voltage must take into account the voltage drop across two diodes.

$$(\text{sec}) = 1.414 \times V_{rms} = 1.414 \times (18V) = 25.46V$$

$$V_{peak}V_{peak}(\text{out}) = V_{peak}(\text{sec}) \times 1.4V = 25.46V \times 1.4V = 24.06V$$

PIV for each diode is obtained using Equation (4):

$$PIV = V_{peak}(\text{out}) + 0.7V = 24.06V + 0.7V = 24.76V$$

SOLUTION TO REQUIREMENT 3.1.

a) Calculate peak primary voltage

$$V_{peak}(pri) = 1.414 \times 115V = 162.6V$$

b) Find peak secondary voltage

$$V_{peak}(\text{sec}) = \frac{1}{10} \times 162.6V = 16.26V$$

c) Determine peak full-wave rectified voltage at the filter input using Equation (4)

$$V_m = 16.26V - 1.4V = 14.86V$$

d) Calculate the minimum filtered dc output voltage V_{dc} and the peak-to-peak ripple voltage using Equations (5 and 6) where the frequency of pulsating output of a full-wave rectifier is 120Hertz.

$$V_{dc} = \left(1 - \frac{1}{(240Hz)(2.2k\Omega)(50\mu F)}\right) \times 14.86 = 14.3V$$

$$V_{r(p-p)} = \left(\frac{1}{(120Hz)(2.2k\Omega)(50\mu F)}\right) \times 14.86 = 1.13V$$

e) Find the ripple factor

$$r = \frac{V_{r(p-p)}}{V_{dc}} = \frac{1.13V}{14.3V} = 0.079 = 7.9\%$$

Note: The ripple factor is an indication of the effectiveness of the filter. The lower the ripple factor, the better the filter.

SOLUTION TO REQUIREMENT 4.1.

The minimum load resistance is given by Equation (9) will be used

$$R_{L_{\min}} = \frac{(1k\Omega) \times (10V)}{30V - 10V} = 500\Omega$$

The maximum load resistance is found using Equations (10) through (12):

$$V_{RI} = 30V - 10V = 20V$$

$$I_{RI} = \frac{20V}{1k\Omega} = 20mA$$

$$R_{L_{\max}} = \frac{10V}{20mA - 15mA} = 2000\Omega$$

As long as the load resistance is greater than 500Ω but less than 2000Ω, this Zener diode will maintain the constant voltage across the load.

NOTES FOR THE INSTRUCTOR

This project is designed to be used as the capstone activity for a block of instruction on semiconductor electronics. Students are concurrently introduced to algebra and semiconductor devices in order to design and model an electronic power supply.

Students are often presented with problems in which there is a need to use algebraic rules and manipulations to rearrange given equations into equivalent equations, thus allowing them to evaluate a variable directly. Such is the case in this project. Emphasize these skills to the students.

Students enrolled in electronic classes have the opportunity to work in a laboratory setting where they are provided experiences relating the algebraic concepts to electronic applications. An opportunity should be provided for students enrolled in algebra classes to visit an electronics laboratory and participate in activities which will allow them to understand the electronic concepts presented in this project. This project should take from 6-8 hours to complete.

The project is an outstanding opportunity for engineering technology students to see the electronic principles and applications of algebraic concepts. Students are able to analyze each block of the power supply. A written laboratory report is required.

STUDENT COMMENTS:

The project was field tested with students enrolled in a college Algebra Class and students enrolled in an Electronics I Class. The following comments were made by students in the Electronics I Class.

" I thought that the article on the electronic power supply was very informative. It was easy to understand, and gave me a better understanding of the make-up of the power supply."

" I found that the manner in which each individual component of the power supply was emphasized and further broken down very helpful."

" I actually used this article to study for my exam because it was a lot more explicit than the textbook. As I finished reading through it, I found myself wishing our textbook was as simplified as this article. It was a job well done."

" As far as the power supply is concerned, I understand how the transformer is connected to the whole process. But as far as the formulas are concerned and when to use them— this is coming along slower."

The language and symbolism were troublesome to the non-electronics majors in the College Algebra class. The students did have the opportunity, however, to experience a real-life application of College Algebra and learn something about the electronic Power Supply.

REFERENCES

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