Lesson 2. VOLTAGE REGULATION AND MULTIPLIERS

LEARNING OBJECTIVES

1. Without the aid of references, describe the operation of the various voltage and current regulators in a power supply in accordance with FM 11-62.

2. Without the aid of references, describe the operation of the various types of voltage multipliers in accordance with FM 11-62.

3. Without the aid of references, trace the flow of A.C. and D.C. in a power supply, from the A.C. input to the D.C. output on a schematic diagram in accordance with FM 11-62.

Peak = Effective (RMS) x 1.414;
Peak = 105 x 1.414 = 148.47 VAC

4201. Operation of Voltage and Regulators

Ideally, the output of most power supplies should be a constant voltage. Unfortunately, this is difficult to achieve. There are two factors which can cause the output voltage to change. First, the a.c. line voltage is not constant. The so-called 115 volts a.c. can vary from about 105 volts a.c. to 125 volts a.c. This means that the peak a.c. voltage to which the rectifier responds can vary from about 148 volts to 177 volts. The a.c. line voltage alone can be responsible for nearly a 20 percent change in the d.c. output voltage. The second factor that can change the d.c. output voltage is a change in the load resistance. In complex electronic equipment, the load can change as circuits are switched in and out. In a television receiver, the load on a particular power supply may depend on the brightness of the screen, the control settings, or even the channel selected.

These variations in load resistance tend to change the applied d.c. voltage because the power supply has a fixed internal resistance. If the load resistance decreases, the internal resistance of the power supply drops more voltage. This causes a decrease in the voltage across the load.

Many circuits are designed to operate with a particular supply voltage. When the supply voltage changes, the operation of the circuit may be adversely affected. Consequently, some types of equipment must have power supplies which produce the same output voltage regardless of changes in the load resistance or changes in the a.c. line voltage. This constant output voltage may be achieved by adding a circuit called the VOLTAGE REGULATOR at the output of the filter. There are many different types of regulators in use today and to discuss all of them would be beyond the scope of this course.

A commonly used FIGURE OF MERIT for a power supply is its PERCENT OF REGULATION. The figure of merit gives us an indication of how much the output voltage changes over a range of load resistance values. The percent of regulation aids in the determination of the type of load regulation needed. Percent of regulation is determined by the equation:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

This equation compares the change in output voltage at the two loading extremes to the voltage produced at full loading. For example, assume that a power supply produces 12 volts when the load current is zero. If the output voltage drops to 10 volts when full load current flows, the percent of regulation is:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

$$= \frac{12 - 10}{10} \times 100$$

$$= \frac{2}{10} \times 100$$

$$= 20\%$$

Ideally, the output voltage should not change over the full range of operation. That is, a 12-volt power supply should produce 12 volts at no load, at full load, and at all points in between. In this case, the percent of regulation would be:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

$$\text{Percent of Regulation} = \frac{12 - 12}{12} \times 100$$

$$\text{Percent of Regulation} = \frac{0}{12} \times 100$$

$$\text{Percent of Regulation} = 0\%$$

Thus, zero-percent load regulation is the ideal situation. It means that the output voltage is constant under all load conditions. While you should strive for zero-percent load regulation, in practical circuits you must settle for something less ideal. Even so, by using a voltage regulator, you can hold the percent of regulation to a very low value.

You should know that the output of a power supply varies with changes in input voltage and circuit load current requirements. Because most electronic equipment requires operating voltages and currents which must remain constant, some form of regulation is necessary. Circuits which maintain power supply voltages or current outputs within specified limits, or tolerances, are called REGULATORS. They are designated as d.c. voltage or d.c. current regulators, depending on their specific application.

Voltage regulator circuits are additions to basic power supply circuits which are made up of rectifier and filter sections (figure 4-30). The purpose of the voltage regulator is to provide an output voltage with little or no variation. Regulator circuits sense changes in output voltages and compensate for the changes. Regulators that maintain voltages within plus or minus (+/-) 0.1 percent are quite common.

Series or shunt voltage regulators. There are two basic types of voltage regulators which are classified as either SERIES or SHUNT, depending on the location or position of the regulating element(s) in relation to the circuit load resistance. Figure 4-31 illustrates these two basic types of voltage regulators. In actual practice the circuitry of regulating devices may be quite complex. Broken lines have been used in the figure to highlight the differences between the series and shunt regulators.

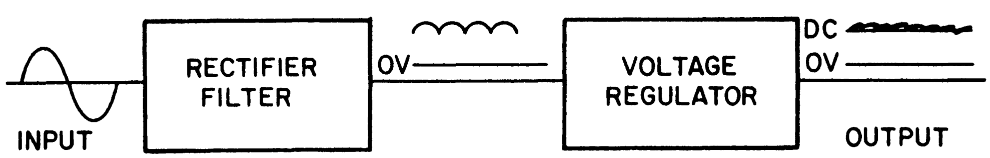


Fig 4-30. Block diagram of a power supply and regulator.

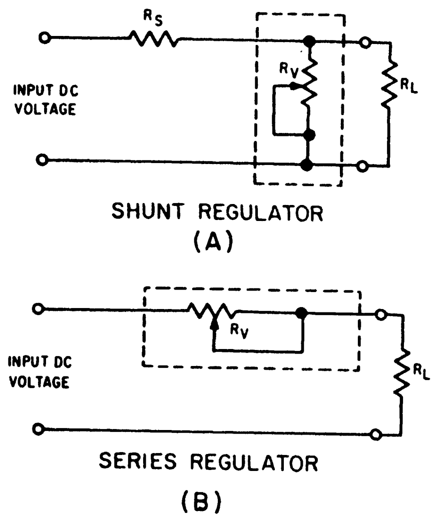


Fig 4-31. Simple series and shunt regulators.

The schematic drawing in view (A) is that of a shunt-type regulator. It is called a shunt-type regulator because the regulating device is connected in parallel with the load resistance. The schematic drawing in view (B) is that of a series regulator. It is called a series regulator because the regulating device is connected in series with the load resistance. Figure 4-32 illustrates the principle of series voltage regulation. As you study the figure, notice that the regulator is in series with the load resistance (R_L) and that the fixed resistor (R_S) is in series with the load resistance.

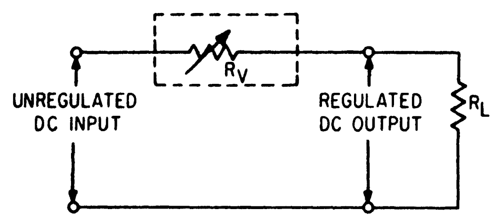


Fig 4-32. Series voltage regulator.

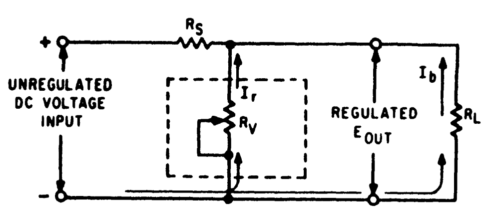


Fig 4-33. Shunt regulator.

You already know the voltage drop across a fixed resistor remains constant unless the current flowing through it varies (increases or decreases). In a shunt regulator, as shown in figure 4-33, output voltage regulation is determined by the current through the parallel resistance of the regulating device (R_V), the load resistance (R_L), and the series resistor (R_S). For now, assume that the circuit is operating under normal conditions, the input is 120 volts d.c., and the desired regulated output is 100 volts d.c. For a 100-volt output to be maintained, 20 volts must be dropped across the series resistor (R_S). If you assume that the value of R_S is 2 ohms, then you must have 10 amperes of current across R_V and R_L. (Remember: $E = IR$.) If the values of the resistance of R_V and R_L are equal, then 5 amperes of current will flow through each resistance (R_V and R_L).

Now, if the load resistance (R_L) increases, the current through R_L will decrease. For example, assume that the current through R_L is now 4 amperes and that the total current across R_S is 9 amperes. With this drop in current, the voltage drop across R_S is 18 volts; consequently, the output of the regulator has increased to 102 volts. At this time, the regulating device (R_V) decreases in resistance, and 6 amperes of current flows through this resistance (R_V). Thus, the total current R_S is once again 10 amperes (6 amperes across R_V; 4 amperes across R_L). Therefore, 20 volts is dropped across R_S causing the output to decrease back to 100 volts. You should know by now that if the load resistance (R_L) increases, the regulating device (R_V) decreases its resistance to compensate for the change. If R_L decreases, the opposite effect occurs and R_V increases.

Now consider the circuit when a decrease in load resistance takes place. When R_L decreases, the current through R_L subsequently increases to 6 amperes. This action causes a total of 11 amperes to flow through R_S which then drops 22 volts. As a result, the output is 98 volts. However, the regulating device (R_V) senses this change and increases its resistance so that less current (4 amperes) flows through R_V. The total current again becomes 10 amperes, and the output is again 100 volts.

From these examples, you should now understand that the shunt regulator maintains the desired output voltage first by sensing the current change in the parallel resistance of the circuit and then by compensating for the change.

Again refer to the schematic shown in figure 4-33 and consider how the voltage regulator operates to compensate for changes in input voltages. You know of course, that the input voltage may vary and that any variation must be compensated for by the regulating device. If an increase in input voltage occurs, the resistance of R_V automatically decreases to maintain the correct voltage division between R_V and R_S. You should see, therefore, that the regulator operates in the opposite way to compensate for a decrease in input voltage.

So far only voltage regulators that use variable resistors have been explained; however, this type of regulation has limitations. Obviously the variable resistor cannot be adjusted rapidly enough to compensate for frequent fluctuations in voltage. Since input voltages fluctuate frequently and rapidly, the variable resistor is not a practical method for voltage regulation. A voltage regulator that operates continuously and automatically to regulate the output voltage without external manipulation is required for practical regulation.

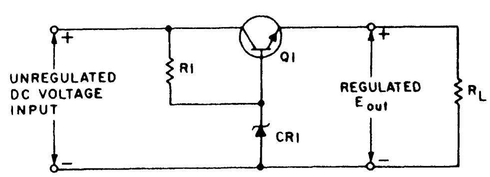


Fig 4-34. Series voltage regulator.

The schematic for a typical series voltage regulator is shown in figure 4-34. Notice that this regulator has a transistor (Q1) in the place of the variable resistor found in figure 4-32. Because the total load current passes through this transistor, it is sometimes called a "pass transistor." Other components which make up the circuit are the current limiting resistor (R1) and the Zener diode (CR1).

Recall that a Zener diode is a diode which blocks current until a specified voltage is applied. Remember also that the applied voltage is called the breakdown, or Zener voltage. Zener diodes are available with different Zener voltages. When the Zener voltage is reached, the Zener diode conducts from its anode to its cathode (with the direction of the arrow).

In this voltage regulator, Q1 has a constant voltage applied to its base. This voltage is often called the reference voltage. As changes in the circuit output voltage occur, they are sensed at the emitter of Q1, producing a corresponding change in the forward bias of the transistor. In other words, Q1 compensates by increasing or decreasing its resistance in order to change the circuit voltage division.

Now, study figure 4-35. Voltages are shown to help you understand how the regulator operates. The Zener used in this regulator is a 15-volt Zener. In this instance, the Zener or breakdown voltage is 15 volts. The Zener establishes the value of the base voltage for Q1. The output voltage will equal the Zener voltage minus a 0.7-volt drop across the forward biased base-emitter junction of Q1, or 14.3 volts. Because the output voltage is 14.3 volts, the voltage drop across Q1 must be 5.7 volts.

Study figure 4-36, view (A), in order to understand what happens when the input voltage exceeds 20 volts. Notice the input and output voltages of 20.1 and 14.4 volts, respectively. The 14.4 output voltage is a momentary deviation, or variation, from the required regulated output voltage of 14.3 and is the result of a rise in the input voltage to 20.1 volts. Since the base voltage of Q1 is held at 15 volts by CR1, the forward bias of Q1 changes to 0.6 volt. Because this bias voltage is less than the normal 0.7 volt, the resistance of Q1 increases, thereby increasing the voltage drop across the transistor to 5.8 volts. The voltage drop restores the output voltage to 14.3 volts. The entire cycle takes only a fraction of a second and, therefore, the change is not visible on an oscilloscope or readily measurable with other standard test equipment.

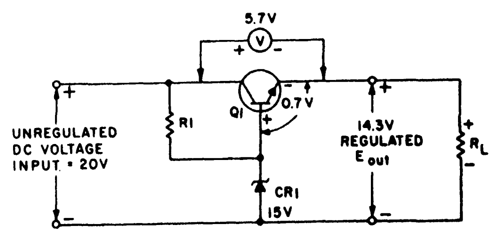
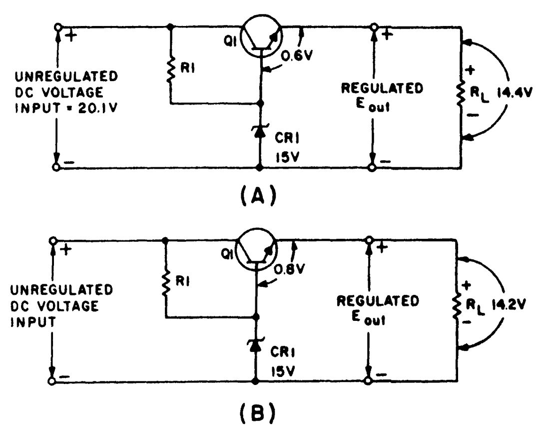


Fig 4-35. Series voltage regulator (with voltages).



A. Increase in output
B. Decrease in output

Fig 4-36. Series voltage regulator.

View (B) is a schematic diagram for the same series voltage regulator with one significant difference. The output voltage is shown as 14.2 volts instead of the desired 14.3 volts. In this case, the load has increased causing a greater voltage drop across R_L to 14.2 volts. When the output decreases, the forward bias of Q1 increases to 0.8 volt because Zener diode CR1 maintains the base voltage of Q1 at 15 volts. This 0.8 volt is the difference between the Zener reference voltage of 15 volts and the momentary output voltage (15 V - 14.2 V = 0.8 V). At this point, the larger forward bias on Q1 causes the resistance of Q1 to decrease, thereby causing the voltage drop across Q1 to return to 5.7 volts. This then causes the output voltage to return to 14.3 volts.

The schematic shown in figure 4-37 is that of a shunt voltage regulator. Notice that Q1 is in parallel with the load. Components of this circuit are identical with those of the series voltage regulator except for the addition of fixed resistor R_S. As you study the schematic, you will see that this resistor is connected in series with the output load resistance. The current limiting resistor (R1) and Zener diode (CR1) provide a constant reference voltage for the base-collector junction of Q1. Notice that the bias of Q1 is determined by the voltage drop across R_S and R1. As you should know, the amount of forward bias across a transistor affects its total resistance. In this case, the voltage drop across R_S is the key to the total circuit operation.

Figure 4-38 is the schematic for a typical shunt-type regulator. Notice that the schematic is identical to the schematic shown in figure 4-37 except that voltages are shown to help you understand the functions of the various components. In the circuit shown, the voltage drop across the Zener diode (CR1) remains constant at 5.6 volts. This means that with a 20-volt input voltage, the voltage drop across R1 is 14.4 volts. With a base-emitter voltage of 0.7 volt, the output voltage is equal to the sum of the voltages across CR1 and the voltage at the base-emitter junction of Q1. In this example, with an output voltage of 6.3 volts and a 20-volt input voltage, the voltage drop across R_S equals 13.7 volts. Study the schematic to understand fully how these voltages are developed. Pay close attention to the voltages shown.

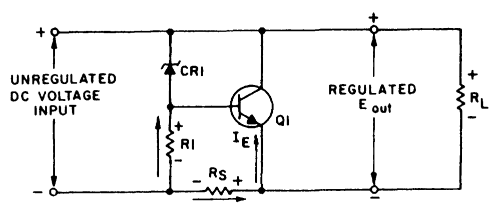


Fig 4-37. Shunt voltage regulator.

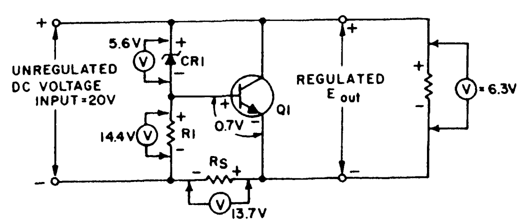
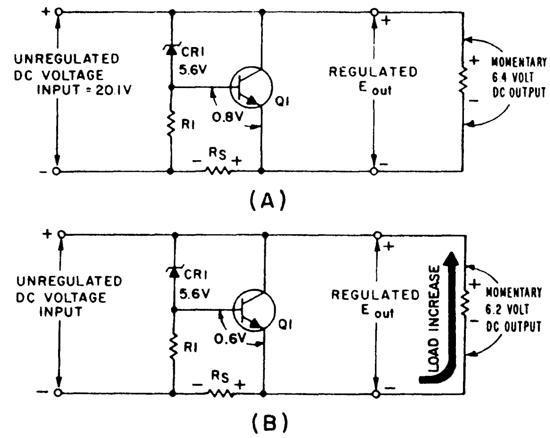


Fig 4-38. Shunt voltage regulator (with voltages).



A. Increase in output voltage
B. Decrease in output voltage

Fig 4-39. Shunt voltage regulator.

Now refer to view (A) of figure 4-39. This figure shows the schematic diagram of the same shunt voltage regulator as that shown in figure 4-38 with an increased input voltage of 20.1 volts. This increases the forward bias on Q1 to 0.8 volt. Recall that the voltage drop across CR1 remains constant at 5.6 volts. Since the output voltage is comprised of the Zener voltage and the base-emitter voltage, the output voltage momentarily increases to 6.4 volts. At this time, the increase in the forward bias of Q1 lowers the resistance of the transistor allowing more current to flow through it. Since this current must also pass through R_s, there is also an increase in the voltage drop across this resistor. The voltage drop across R_s is now 13.8 volts and, therefore, the output voltage is reduced to 6.3 volts. Remember, this change takes place in a fraction of a second.

Study the schematic shown in view (B). Although this schematic is identical to the other shunt voltage schematics previously illustrated and discussed, the output voltage is different. The load current has increased causing a momentary drop in voltage output to 6.2 volts. Recall that the circuit was designed to ensure a constant output voltage of 6.3 volts. Since the output voltage is less than that required, changes occur in the regulator to restore the output to 6.3 volts. Because of the 0.1-volt drop in the output voltage, the forward bias of Q1 is now 0.6 volt. The decrease in the forward bias increases the resistance of the transistor, thereby reducing the current flow through Q1 by the same amount that the load current increased. The current flow through R_s returns to its normal value and restores the output voltage to 6.3 volts.

Current regulators. You should now know how voltage regulators work to provide constant output voltage. In some circuits it may be necessary to regulate the current output. The circuitry which provides a constant current output is called a constant current regulator or just CURRENT REGULATOR. The schematic shown in figure 4-40 is a simplified schematic for a current regulator. The variable resistor shown on the schematic is used to illustrate the concept of current regulation. You should know from your study of voltage regulators that a variable resistor does not respond quickly enough to compensate for the changes. Notice that an ammeter has been included in this circuit to indicate that the circuit shown is that of a current regulator. When the circuit functions properly, the current reading of the ammeter remains constant. In this case the variable resistor (R_V) compensates for changes in the load or d.c. input voltage. Adequate current regulation results in the loss of voltage regulation. Studying the schematic shown, you should recall that any increase in load resistance causes a drop in current. To maintain a constant current flow, the resistance of R_V must be reduced whenever the load resistance increases. This causes the total resistance to remain constant. An increase in the input voltage must be compensated for by an increase in the resistance of R_V, thereby maintaining a constant current flow. The operation of a current regulator is similar to that of a voltage regulator. The basic difference is that one regulates current and the other regulates voltage.

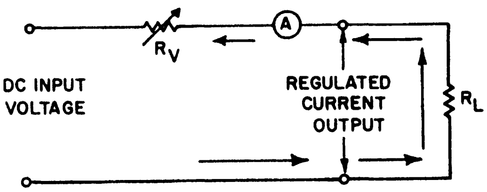


Fig 4-40. Current regulator.

Since use of a variable resistor is not a practical way to control current fluctuation, or variation, a transistor and a Zener diode, together with necessary resistors are used. Recall that the Zener diode provides a constant reference voltage. The schematic shown in figure 4-41 is that of a current regulator circuit. Except for the addition of R1, the circuit shown in the figure is similar to that of a series voltage regulator. The resistor is connected in series with the load and senses any current changes in the load. Notice the voltage drop across R1 and the negative voltage polarity applied to the emitter of Q1. The voltage polarity is a result of current flowing through R1, and this negative voltage opposes the forward bias for Q1; however, since the regulated voltage across CR1 has an opposite polarity, the actual bias of the transistor is the difference between the two voltages. You should see therefore that the purpose of R2 is to function as a current- limiting resistor for the Zener diode.

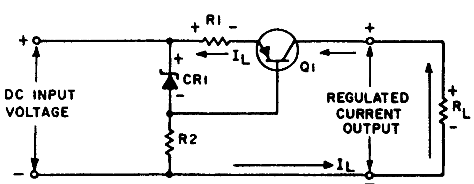


Fig 4-41. Current regulator.

The purpose of a current regulator is to provide a constant current regardless of changes in the input voltage or load current. The schematic shown in figure 4-42 is that of a circuit designed to provide a constant current of 400 milliamperes. Voltmeters are shown in the schematic to emphasize the voltage drops across specific components. These voltages will help you understand how the current regulator operates. The voltage drop across the base- emmiter junction of Q1 is 0.6 volt. This voltage is the difference between the Zener voltage and the voltage drop across R1. The 0.6-volt forward bias of Q1 permits proper operation of the transistor. The output voltage across R_L is 6 volts as shown by the voltmeter. With a regulated current output of 400 milliamperes, the transistor resistance (R_{Q1}) is 9 ohms. This can be proved by using Ohm's law and the values shown on the schematic. In this case, current (I) is equal to the voltage drop (E) divided by the resistance (R). Therefore, 12 volts divided by 30 ohms equals 0.4 ampere, or 400 milliamperes.

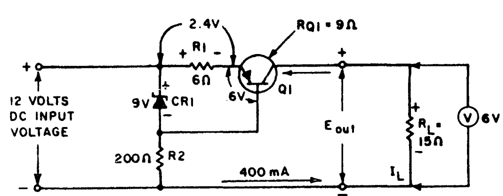


Fig 4-42. Current regulator (with circuit values).

Since you are familiar with the basic current regulating circuitry, let's examine in detail how the various components work to maintain the constant 400-milliamperes output. Refer to the schematic shown in figure 4-43. Remember, a decrease in load resistance causes a corresponding increase in current flow. In the example shown, the load resistance R_L has dropped from 15 ohms to 10 ohms. This results in a larger voltage drop across R1 because of the increased current flow. The voltage drop has increased from 2.4 volts to 2.5 volts. Of course, the voltage drop across CR1 remains constant at 9 volts due to its regulating ability. Because of the increased voltage drop across R1, the forward bias on Q1 is now 0.5 volt. Since the forward bias of Q1 has decreased, the resistance of the transistor increases from 9 ohms to 14 ohms. Notice that the 5-ohm increase in resistance across the transistor corresponds to the 5-ohm decrease in the load resistance. Thus, the total resistance around the outside loop of the circuit remains constant. Since the circuit is a current regulator, you know that output voltage will vary as the regulator maintains a constant current output. In the figure, the voltage output is reduced to 4 volts, which is computed by multiplying current (I) times resistance (R) (400 mA x 10 ohms = 4 volts).

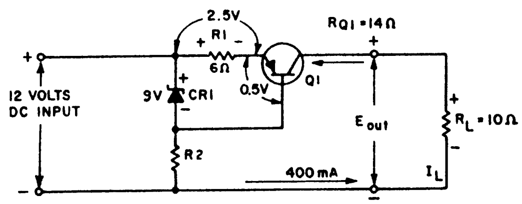


Fig 4-43. Current regulator (with a decrease in R_L).

4202. Types of Voltage Multipliers

You may already know how a transformer functions to increase or decrease voltage. You may also have learned that a transformer secondary may provide one or several a.c. voltage outputs which may be greater or less than the input voltage. When voltages are stepped up, current is decreased; when voltages are stepped down, current is increased.

Another method for increasing voltages is known as voltage multiplication. VOLTAGE MULTIPLIERS are used primarily to develop high voltages where low current is required. The most common application of the high voltage outputs of voltage multipliers is the anode of cathode-ray tubes (CRT) which are used for radar scope presentations, oscilloscope presentations, or TV picture tubes. The d.c. output of the voltage multiplier ranges from 1000 volts to 30,000 volts. The actual voltage depends upon the size of the CRT and its equipment application.

Voltage multipliers may also be used as primary power supplies where a 177-volt a.c. input is rectified to pulsating d.c. This d.c. output voltage may be increased (through use of a voltage multiplier) to as much as 1000 volts d.c. This voltage is generally used as the plate or screen grid voltage for electron tubes.

If you have studied transformers, you may have learned that when voltage is stepped up, the output current decreases. This is also true of voltage multipliers. Although the measured output voltage of a voltage multiplier may be several times greater than the input voltage, once a load is connected the value of the output voltage decreases. Also any small fluctuation of load impedance causes a large fluctuation in the output voltage of the multiplier. For this reason, voltage multipliers are used only in special applications where the load is constant and has a high impedance or where input voltage stability is not critical.

Voltage multipliers may be classified as voltage doublers, triplers, or quadruplers. The classification depends on the ratio of the output voltage to the input voltage. For example, a voltage multiplier that increases the peak input voltage twice is called a voltage doubler. Voltage multipliers increase voltages through the use of series-aiding voltage sources. This can be compared to the connection of dry cells (batteries) in series.

The figures used in the explanation of voltage multipliers show a transformer input, even though for some applications a transformer is not necessary. The input could be directly from the power source or line voltage. This, of course, does not isolate the equipment from the line and creates a potentially hazardous condition. Most military equipment uses transformers to minimize this hazard.

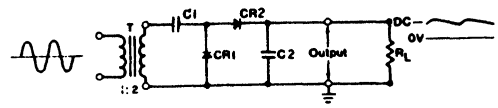
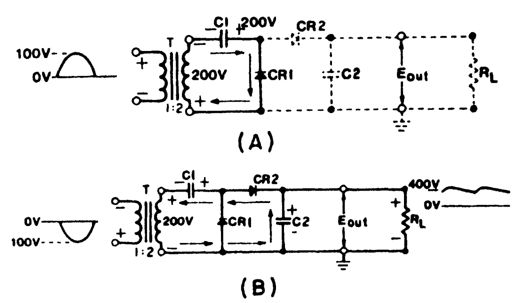


Fig 4-44. Half-wave voltage doubler.

Figure 4-44 shows the schematic for a half-wave voltage doubler. Notice the similarities between this schematic and those of half-wave voltage rectifiers with which you are already familiar. In fact, the doubler shown is made up of two half-wave voltage rectifiers. C1 and CR1 make up one half-wave rectifier, and C2 and CR2 make up the other. The schematic of the first half-wave rectifier is indicated by the dark lines in view (A) of figure 4-45. The dotted lines and associated components represent the other half-wave rectifier and load resistor.

Notice that C1 and CR1 work exactly like a half-wave rectifier. During the positive alternation of the input cycle (view A), the polarity across the secondary winding of the transformer is as shown. Note that the top of the secondary is negative. At this time CR1 is forward biased (cathode negative in respect to the anode). This forward bias causes CR1 to function like a closed switch and allows current to flow the path indicated by the arrows. At this time, C1 charges to the peak value of the input voltage, or 200 volts, with the polarity shown.

During the period when the input cycle is negative, as shown in view (B), the polarity across the secondary of the transformer is reversed. Note specifically that the top of the secondary winding is now positive. This condition now forward biases CR2 and reverse biases CR1. A series circuit now exists consisting of C1, CR2, C2 and the secondary of the transformer. The current flow is indicated by the arrows. The secondary voltage of the transformer now aids the voltage on C1. This results in a pulsating d.c. voltage of 400 volts, as shown by the waveform. The effect of series aiding is comparable to the connection of two 200-volt batteries in series. As shown in figure 4-46, C2 charges to the sum of these voltages, or 400 volts.



A. Positive alternation
B. Negative alternation

Fig 4-45. Rectifier action of CR1 and CR2.

The schematic shown in figure 4-47 is an illustration of a half-wave voltage tripler. When you compare figures 4-46 and 4-47, you should see that the circuitry is identical except for the additional parts, components, and circuitry shown by the dotted lines. (CR3, C3 and R2 make up the additional circuitry.) By themselves, CR3, C3, and R2 make up a half-wave rectifier. Of course, if you remove the added circuitry, you will once again have a half-wave voltage doubler.

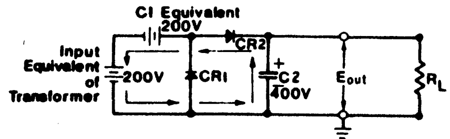


Fig 4-46. Series-aiding sources.

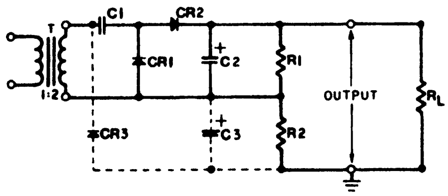


Fig 4-47. Half-wave voltage tripler.

View (A) of figure 4-48 shows the schematic for the voltage tripler. Notice that CR3 is forward biased and functions like a closed switch. This allows C3 to charge to a peak voltage of 200 volts at the same time C1 is also charging to 200 volts.

The other half of the input cycle is shown in view (B). C2 is charged to twice the input voltage, or 400 volts, as a result of the voltage-doubling action of the transformer and C1. At this time, C2 and C3 are used as series-aiding devices, and the output voltage increases to the sum of their respective voltages, or 600 volts. R1 and R2 are proportional according to the voltages across C2 and C3. In this case, there is a 2 to 1 ratio.

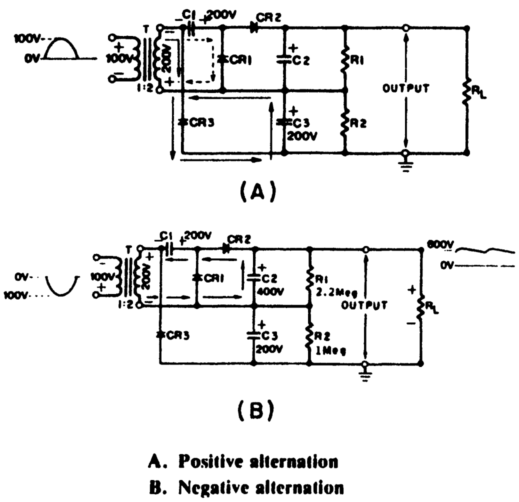


Fig 4-48. Voltage tripler.

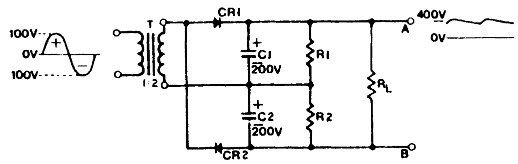


Fig 4-49. Full-wave voltage doubler.

The circuit shown in figure 4-49 is that of a full-wave voltage doubler. The main advantage of a full-wave doubler over a half-wave doubler is better voltage regulation, as a result of reduction in the output ripple amplitude and an increase in the ripple frequency. The circuit is, in fact, two half-wave rectifiers. These rectifiers function as series-aiding devices except in a slightly different way. During the alternation when the secondary of the transformer is positive at the top C1 charges to 200 volts through CR1. Then, when the transformer secondary is negative at the top, C2 charges to 200 volts through CR2. R1 and R2 are of equal value, balancing resistors which stabilize the charges of the two capacitors. Resistive load R_L is connected across C1 and C2 so that R_L receives the total charge of both capacitors. The output voltage is +400 volts when measured at the top of R_L, or point "A" with respect to point "B." If the output is measured at the bottom of R_L, it is -400 volts. Either way, the output is twice the peak value of the a.c. secondary voltage. As you may have guessed, the possibilities for voltage multiplication are almost unlimited.

The main disadvantage of a series regulator is that the pass transistor is in series with the load. If a short develops in the load, a large amount of current will flow in the regulator circuit. The pass transistor can be damaged by this excessive current flow. You can place a fuse in the circuit, but in many cases, the transistor will be damaged before the fuse blows. The best way to protect this circuit is to limit the current automatically to a safe value. A series regulator with a current-limiting circuit is shown in figure 4-50. You should recall that in order for a silicon NPN transistor to conduct, the base must be between 0.6 volt to 0.7 volt more positive than the emitter. Resistor R4 will develop a voltage drop of 0.6 volt when the load current reaches 600 milliamperes. This is illustrated using Ohm's law:

$$I = \frac{E}{R} \quad \frac{0.6 \text{ volt}}{1 \text{ ohm}} = .6 \text{ ampere or } 600 \text{ milliamperes}$$

When load current is below 600 milliamperes, the base-to-emitter voltage on Q2 is not high enough to allow Q2 to conduct. With Q2 cut off, the circuit acts like a series regulator.

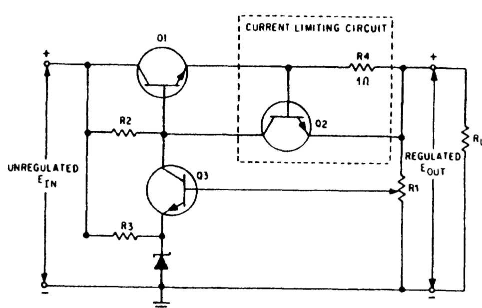


Fig 4-50. Series regulator with current limiting.

When the load current increases above 600 milliamperes, the voltage drop across R4 increases to more than 0.6 volt. This causes Q2 to conduct through resistor R2, thereby decreasing the voltage on the base of pass transistor Q1. This action causes Q1 to conduct less. Therefore, the current cannot increase above 600 to 700 milliamperes.

By increasing the value of R4, you can limit the current to almost any value. For example, a 100-ohm resistor develops a voltage drop of 0.6 volt at 6 milliamperes of current. You may encounter current-limiting circuits that are more sophisticated, but the theory of operation is always the same. So, if you understand this circuit, the others should be no problem.

EXERCISE: Complete items 1 through 13 by performing the action required. Check your responses against those listed at the end of this study unit.

1. Circuits which maintain constant voltage or current outputs are called d.c. voltage or d.c. current ______________________________

2. The purpose of a voltage regulator is to provide an output voltage with little or no ______________________________

3. The two basic types of voltage regulators are:

   a. ______________________________

   b. ______________________________

4. When a series voltage regulator is used to control output voltages, any increase in the input voltage results in ____________________ in the resistance of the regulating device.

5. The shunt-type voltage regulator is connected in ____________________ with the load resistance.

6. In figure 4-37, the voltage drop across R_S and R_L determines the amount of base-emitter ____________________ for Q1.

7. In figure 4-39, view (A), when there is an increase in the input voltage, the forward bias of Q1 ____________________.

8. In view (B) of figure 4-39, when the load current increases and the output voltage momentarily drops, the resistance of Q1 ____________________ to compensate.

9. In figure 4-40, when there is an increase in the load resistance (R_L), the resistance of R_V ____________________ to compensate for the change.

10. In figure 4-43 any decrease in the base-emitter forward bias across Q1 results in ____________________ in the resistance of the transistor.

11. A half-wave voltage doubler is made up of how many half-wave rectifiers?

    ____

12. If a half-wave rectifier is added to a half-wave voltage doubler, the resulting circuit is a voltage ______________________________

13. In a full-wave voltage doubler, are the capacitors connected in series or in parallel with the output load?

    ____