Diode Circuits

A. Diode Circuits

1. Half-Wave Rectification

   a. A rectifier is an electrical device that converts alternating current to direct current, a process known as rectification. Rectifiers are used as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves, and other technologies.

   b. When just one diode is used to rectify AC (by blocking the negative or positive portion of the waveform) the difference between the term diode and the term rectifier is merely one of usage, i.e., the term rectifier describes a diode that is being used to convert AC to DC. Almost all rectifiers comprise a number of diodes in a specific arrangement for more efficiently converting AC to DC than is possible with just a single diode. Before the development of solid state rectifiers, vacuum tube diodes and copper oxide or selenium rectifier stacks were used.

   c. Early radio receivers called crystal sets, used a "cat's whisker" of fine wire pressing on a crystal of galena (lead sulfide) to serve as a point contact rectifier or "crystal detector". In gas heating systems flame rectification can be used to detect a flame. Two metal electrodes in the outer layer of the flame provide a current path and rectification of an applied alternating voltage, but only while the flame is present.

   d. A half wave rectifier is a special case of a clipper. In half wave rectification, either the positive or negative half of the AC wave is passed easily while the other half is blocked, depending on the polarity of the rectifier. Because only one half of the input waveform reaches the output, it is very inefficient if used for power transfer. Half wave rectification can be achieved with a single diode in a one phase supply.

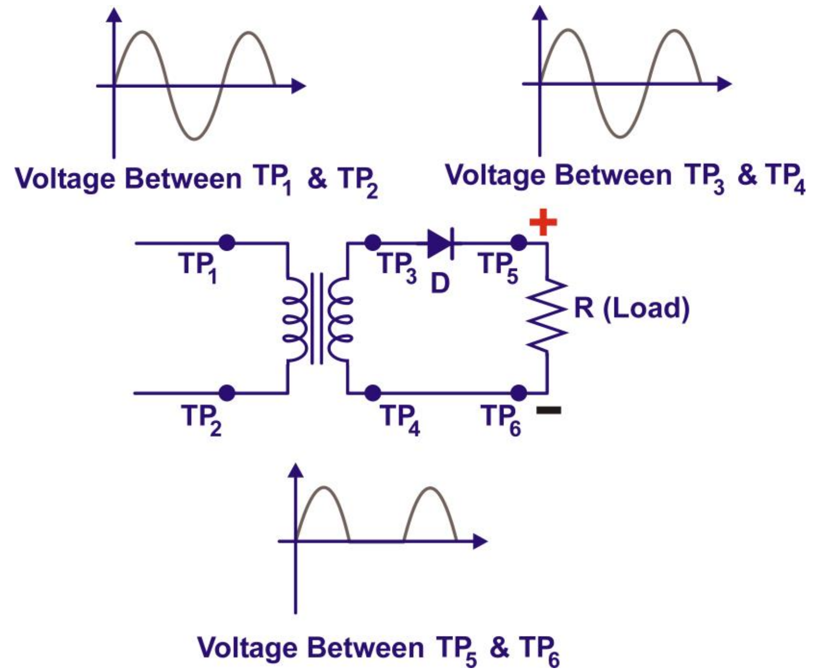

Figure 1, Diode-Circuits-001 Semiconductor Half-Wave Rectifier

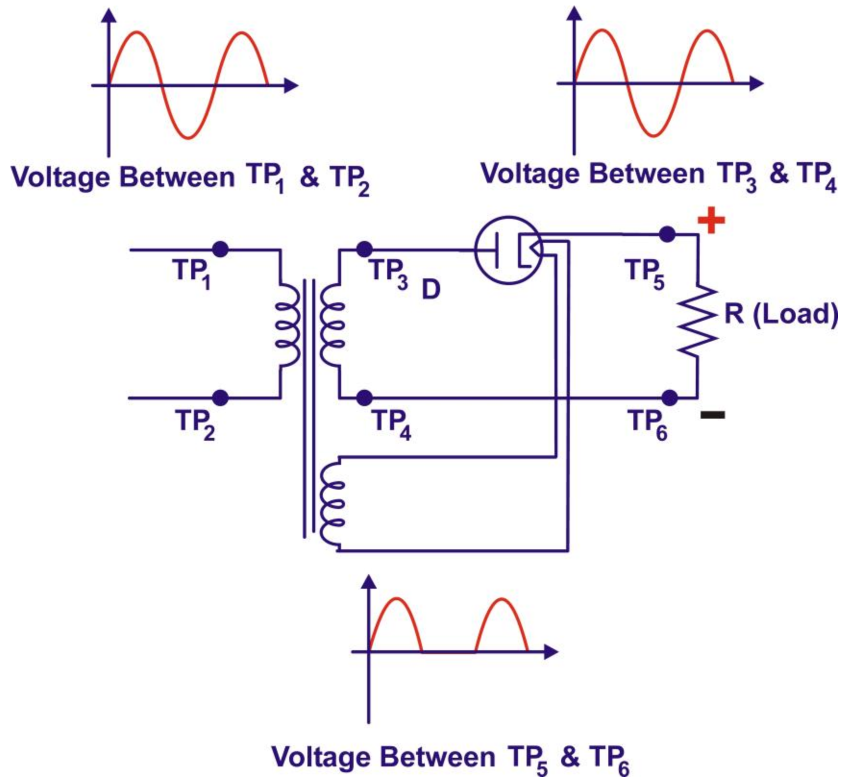

Figure 2, Diode Circuits-002 Vacuum Tube Half-Wave Rectifier

e. For most power applications, half-wave rectification is insufficient for the task. The harmonic content of the rectifier's output waveform is very large and consequently difficult to filter. Furthermore, AC power source only works to supply power to the load once every half-cycle, meaning that much of its capacity is unused. Half-wave rectification is, however, a very simple way to reduce power to a resistive load. Some two-position lamp dimmer switches apply full AC power to the lamp filament for "full" brightness and then half-wave rectify it for a lesser light output:

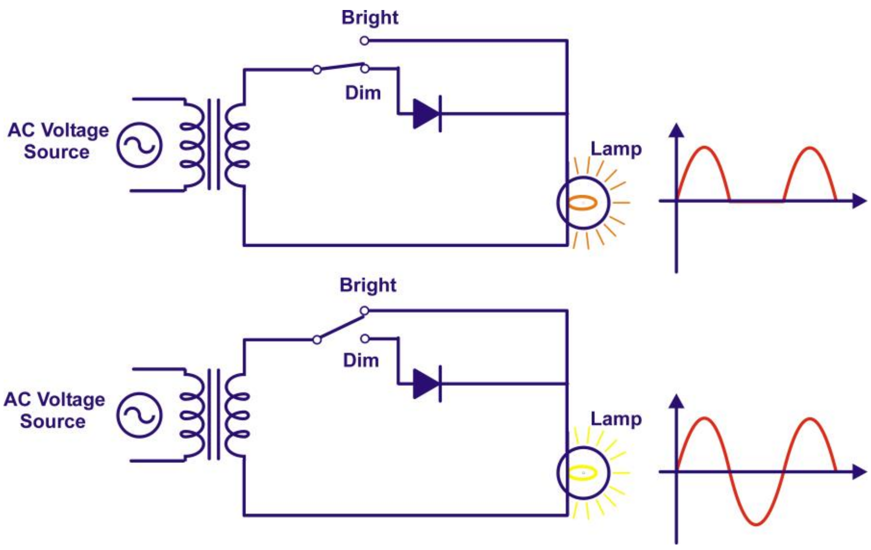

Figure 3, Diode-Circuits-003 Half-Wave Dimmer

f. In the "Dim" switch position, the incandescent lamp receives approximately one-half the power it would normally receive operating on Full-Wave AC. Because the half-wave rectified power pulses far more rapidly than the filament has time to heat up and cool down, the lamp does not blink. Instead, its filament merely operates at a lesser temperature than normal, providing less light output. This principle of "pulsing" power rapidly to a slow-responding load device in order to control the electrical power sent to it is very common in the world of industrial electronics. Since the controlling device (the diode, in this case) is either fully conducting or fully nonconducting at any given time, it dissipates little heat energy while controlling load power, making this method of power control very energy-efficient. This circuit is perhaps the crudest possible method of pulsing power to a load, but it suffices as a proof-of-concept application.

2. Full-Wave Rectification (Center Tap 2 Diode)

a. If we need to rectify AC power so as to obtain the full use of both half-cycles of the sine wave, a different rectifier circuit configuration must be used. Such a circuit is called a Full-Wave rectifier. One type of Full-Wave rectifier, called the center-tap design, uses a transformer with a center-tapped secondary winding and two diodes, like this:

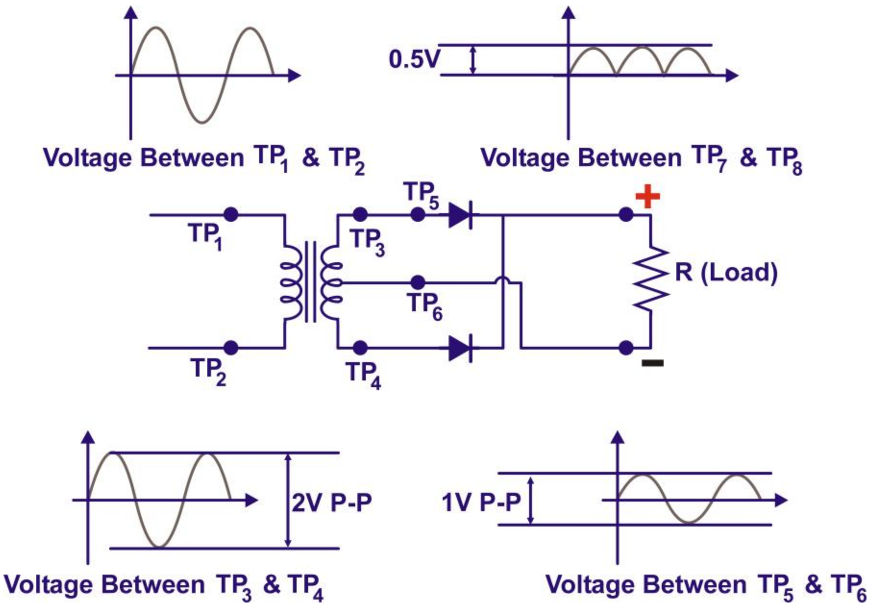

Figure 4, Diode-Circuits-004 Full-Wave Rectifier Center Tap (2-Diode)

b. This circuit's operation is easily understood one half-cycle at a time. Consider the first half-cycle, when the source voltage polarity is positive (+) on top and negative (-) on bottom. At this time, only the top diode is conducting; the bottom diode is blocking current, and the load "sees" the first half of the sine wave, positive on top and negative on bottom. Only the top half of the transformer's secondary winding carries current during this half-cycle:

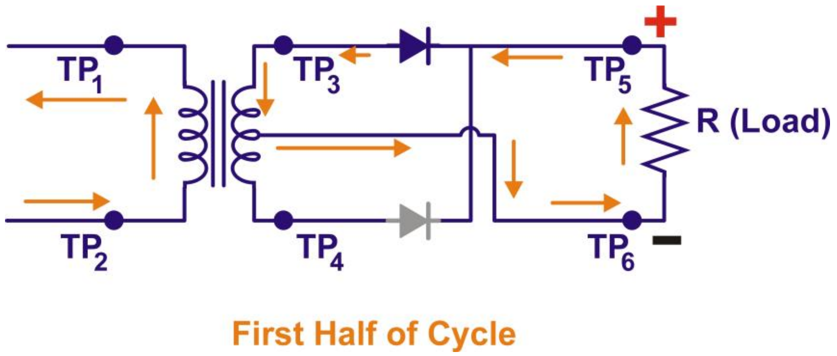

Figure 5, Diode-Circuits-005 Full-Wave Rectifier Center Tap Half-Cycle Flow A

c. During the next half-cycle, the AC polarity reverses. Now, the other diode and the other half of the transformer's secondary winding carry current while the portions of the circuit formerly carrying current during the last half-cycle sit idle. The load still "sees" half of a sine wave, of the same polarity as before: positive on top and negative on bottom:

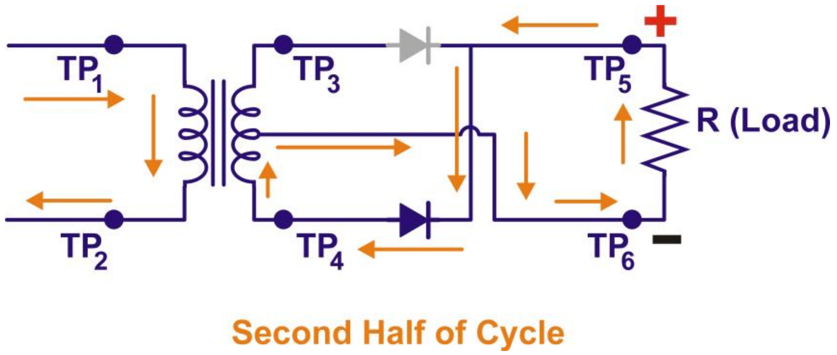

Figure 6, Diode-Circuits-006 Full-Wave Rectifier Center Tap Half-Cycle Flow B

d. One disadvantage of this Full-Wave rectifier design is the necessity of a transformer with a center-tapped secondary winding. If the circuit in question is one of high power, the size and expense of a suitable transformer is significant. Consequently, the center-tap rectifier design is seen only in low-power applications.

3. Full-Wave Rectification Bridge (4 diode)

   a. Another, more popular Full-Wave rectifier design exists, and it is built around a four-diode bridge configuration. For obvious reasons, this design is called a Full-Wave bridge:

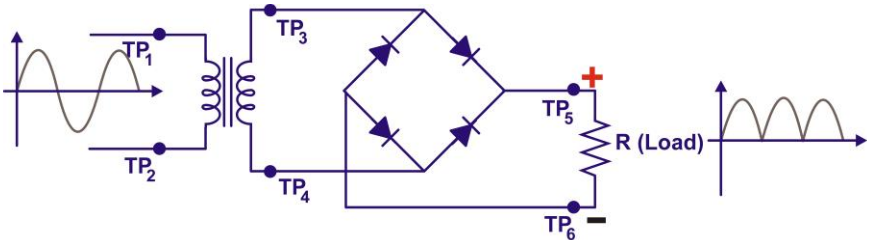

Figure 7, Diode-Circuits-007 Full-Wave Rectifier Bridge (4 Diode)

   b. Current directions in the Full-Wave bridge rectifier circuit are as follows for each half-cycle of the AC waveform:

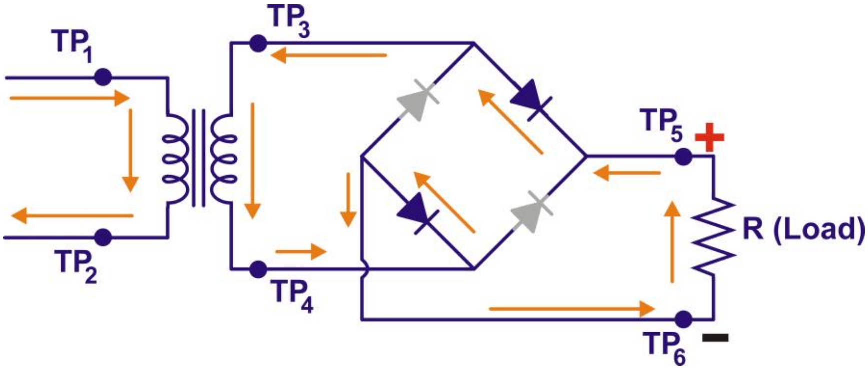

Figure 8, Diode-Circuits-008 Full-Wave Rectifier Bridge Half-Cycle Flow A

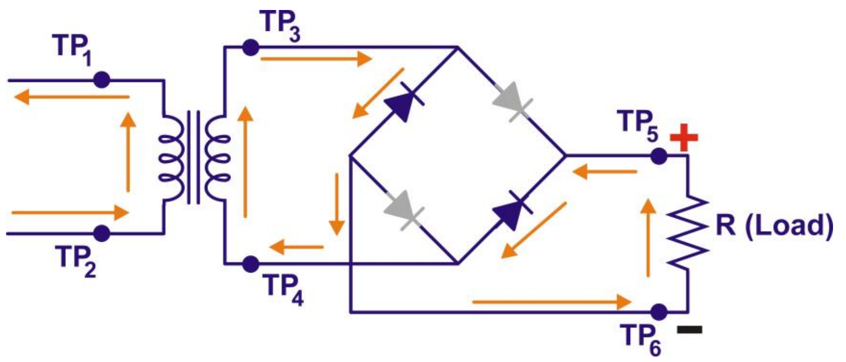

Figure 9, Diode-Circuits-009 Full-Wave Rectifier Bridge Half-Cycle Flow B

c. Redrawing the circuit may help understand it.

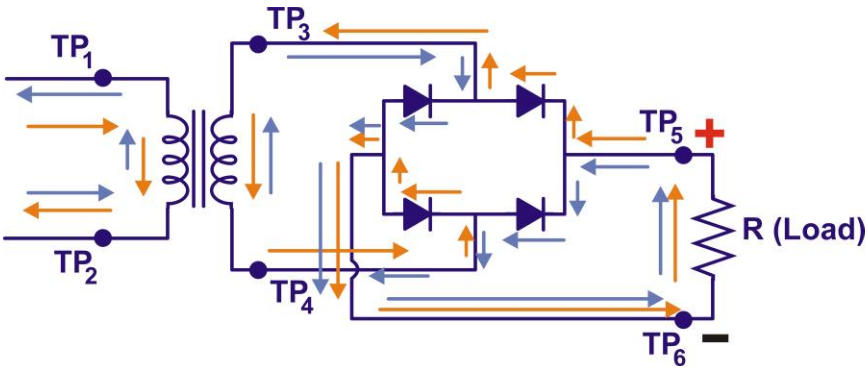

Figure 10, Diode-Circuits-010 Full-Wave Rectifier Bridge Redrawn

4. Polyphase Rectification

   a. When polyphase AC is rectified, the phase-shifted pulses overlap each other to produce a DC output that is much "smoother" (has less AC content) than that produced by the rectification of single-phase AC. This is a decided advantage in high-power rectifier circuits, where the sheer physical size of filtering components would be prohibitive but low-noise DC power must be obtained.

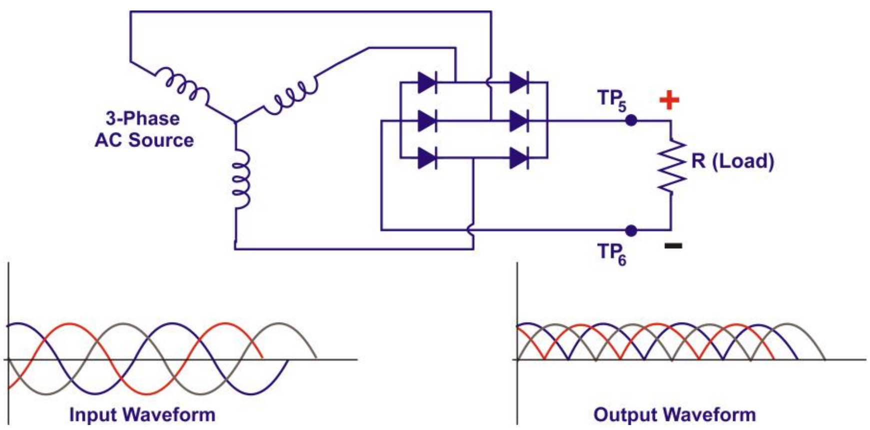

Figure 11, Diode-Circuits-011 Three Phase Full-Wave Rectifier Bridge

b. Three-Phase Rectification

1) Each three-phase line connects between a pair of diodes: one to route power to the positive (+) side of the load, and the other to route power to the negative (-) side of the load. Polyphase systems with more than three phases are easily accommodated into a bridge rectifier scheme.

5. Six Phase Rectification

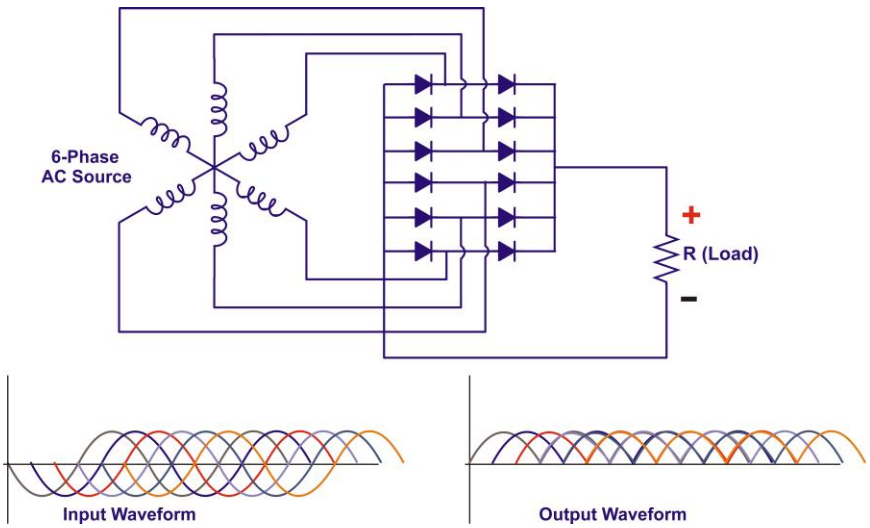

Figure 12, Diode-Circuits-012 Six Phase Full-Wave Rectifier Bridge

1) In any case of rectification -- single-phase or polyphase -- the amount of AC voltage mixed with the rectifier's DC output is called ripple voltage. In most cases, since "pure" DC is the desired goal, ripple voltage is undesirable. If the power levels are not too great, filtering networks may be employed to reduce the amount of ripple in the output voltage.

2) Sometimes, the method of rectification is referred to by counting the number of DC "pulses" output for every 360^{o} of electrical "rotation." A single-phase, half-wave rectifier circuit, then, would be called a 1-pulse rectifier, because it produces a single pulse during the time of one complete cycle (360^{o}) of the AC waveform. A single-phase, full-wave rectifier (regardless of design, center-tap or bridge) would be called a 2-pulse rectifier, because it outputs two pulses of DC during one AC cycle's worth of time. A three-phase full-wave rectifier would be called a 6-pulse unit.

3) Modern electrical engineering convention further describes the function of a rectifier circuit by using a three-field notation of phases, ways, and number of pulses. A single-phase, half-wave rectifier circuit is given the somewhat cryptic designation of 1Ph1W1P (1 phase, 1 way, 1 pulse), meaning that the AC supply voltage is single-phase, that current on each phase of the AC supply lines moves in one direction (way) only, and that there is a single pulse of DC produced for every 360o of electrical rotation. A single-phase, full-wave, center-tap rectifier circuit would be designated as 1Ph1W2P in this notational system: 1 phase, 1 way or direction of current in each winding half, and 2 pulses or output voltage per cycle. A single-phase, full-wave, bridge rectifier would be designated as 1Ph2W2P: the same as for the center-tap design, except current can go both ways through the AC lines instead of just one way. The three-phase bridge rectifier circuit shown earlier would be called a 3Ph2W6P rectifier.

4) Is it possible to obtain more pulses than twice the number of phases in a rectifier circuit? The answer to this question is yes: especially in polyphase circuits. Through the creative use of transformers, sets of full-wave rectifiers may be paralleled in such a way that more than six pulses of DC are produced for three phases of AC. A 30^{o} phase shift is introduced from primary to secondary of a three-phase transformer when the winding configurations are not of the same type. In other words, a transformer connected either Y-Δ or Δ-Y will exhibit this 30^{o} phase shift, while a transformer connected Y-Y or Δ-Δ will not. This phenomenon may be exploited by having one transformer connected Y-Y feed a bridge rectifier, and have another transformer connected Y-Δ feed a second bridge rectifier, then

parallel the DC outputs of both rectifiers. Since the ripple voltage waveforms of the two rectifiers' outputs are phase-shifted 30^{o} from one another, their superposition results in less ripple than either rectifier output considered separately: 12 pulses per 360^{o} instead of just six:

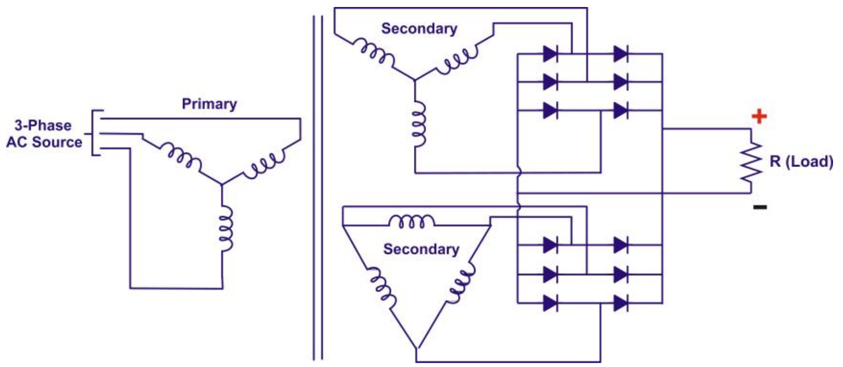

Figure 13, Diode-Circuits-013 Three Phase 2 Way 12 Pulse Rectifier

6. Diode Clamps
   a. A clamping circuit is a circuit that reproduces the input signal on the output side by shifting it either up or down.
   b. Let us consider the circuit given in Figure 2.56. When the diode conducts, the output voltage is equal to the forward voltage of the diode. For an ideal diode, the output voltage is zero when it conducts. Let $v_D(t)$ be the voltage across the diode when it conducts. Then, the current in the diode is $i_D(t)=\frac{v_s(t)-V_B-v_D(t)}{R}$.
   c. From this equation, it is evident that the diode will conduct as long as $v_s(t)\ge V_B+v_D(t)$ and the output voltage across the diode is $v_o(t)=v_D(t)$
   d. For an ideal diode $v_o(t)=0$ because $v_D(t)= 0$.

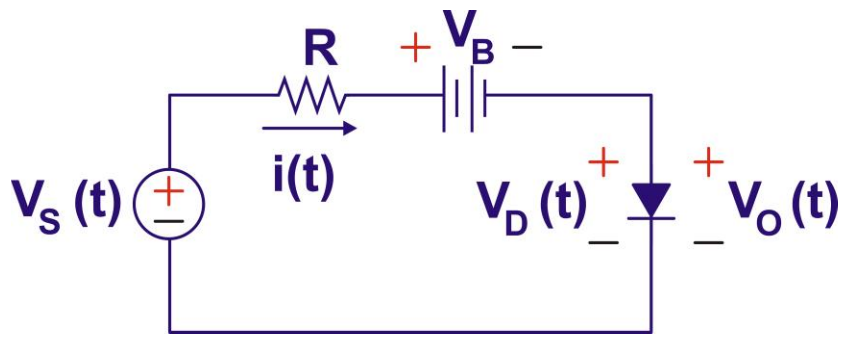

Figure 14, Diode-Circuits-014 Clamping Circuit

e. Since we want the input voltage to be reproduced exact ly without any clipping, the maximum value of $V_S(t)$ must not be greater than V_B . If $V_S(t)$ is greater than V_B , then the circuit will also behave as a limiter. On the other hand, when is $V_S(t)$ less than V_B , the diode does not conduct . The output voltage is simply the input voltage minus V_B . Thus, the output waveform has been shift down by V_B as shown in Figure "Diode-Circuits-015" when V_{SM}, the maximum value of $V_S(t)$, is less than (V_B $V_D(t)$).

f. The input and output waveforms are given in Figure 46a and b, respectively. note that the waveform is shifted in the direct ion of the arrow of the diode. This is a good way to remember the shift.

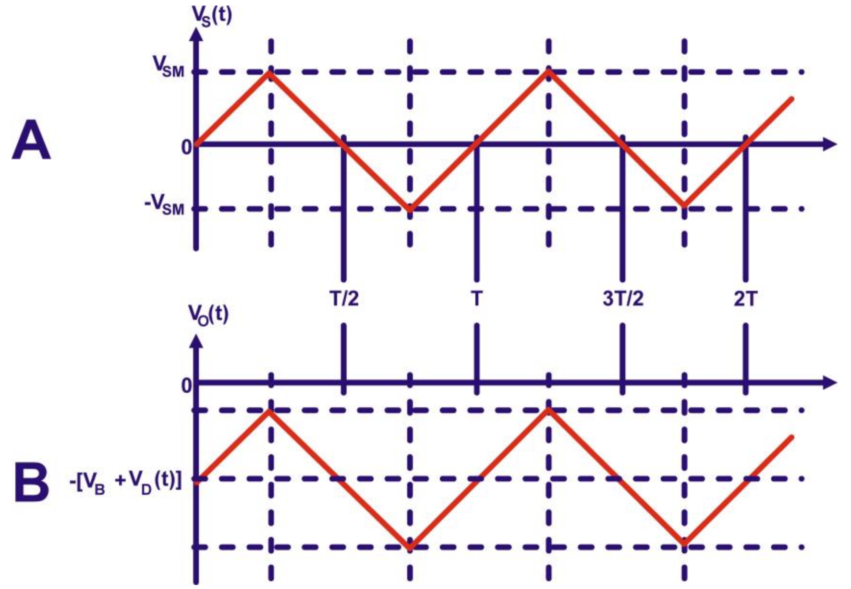

Figure 15, Diode-Circuits-015 Clamped Output

g. In practice, the clamping circuit uses a capacitor instead of a dc voltage source as shown in Figure "Diode-Circuits-016". The only condition is that the time constant RC of the circuit must be greater than the time period of the waveform T so that capacitor barely discharges during its discharging process. For all practical purposes, we assume that this condition is met as long as RC ≥ 10 T.

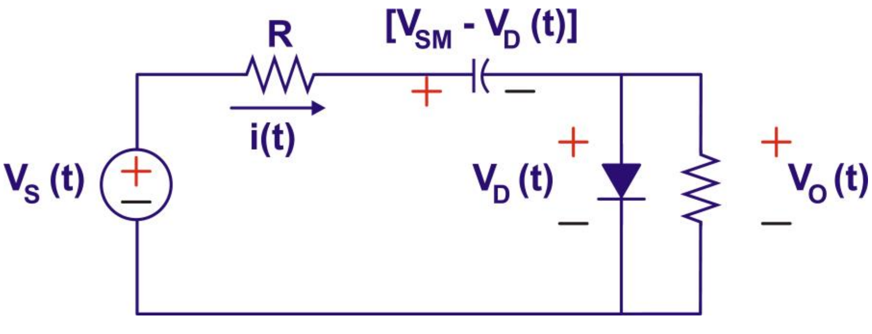

Figure 16, Diode-Circuits-016 Clamping Circuit With Capacitor

h. This is how the circuit in Figure "Diode-Circuits-016" works. During the positive half -cycle of the input waveform, the diode is forward biased and the capacitor charges to a maximum positive voltage of $[V_{SM}\ V_D(t)]$ − with the polarity as shown. Note that V_{SM} is the maximum value of the input voltage and $V_D(t)$ is the corresponding voltage across the diode.

i. During the negative half-cycle, the diode is reversed biased. The capacitor will now tend to discharge through R and the voltage source $V_S(t)$ in an attempt to charge in the opposite direction. If the time constant, RC, is much greater than the time-period of the input waveform, the capacitor discharge is almost negligible. Thus, the voltage across the capacitor stays almost at its maximum value. In other words, the capacitor behaves like a constant voltage source very similar to that in Figure "Diode-Circuits-014".

j. Consider the circuit shown in Figure "Diode-Circuits-017" with a time constant RC much greater than the time period T of the input waveform. For all practical purposes, let us assume that this condition is met as long as RC ≥ 10 T.

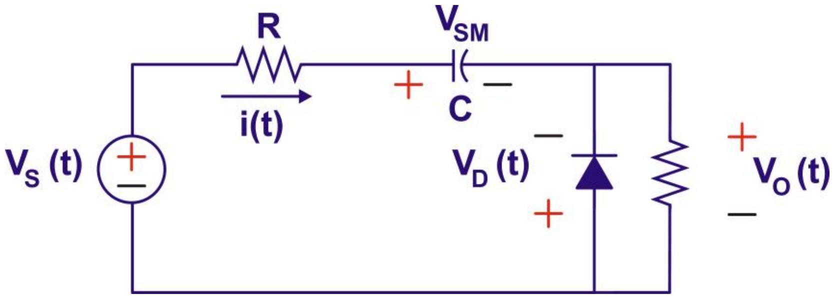

Figure 17, Diode-Circuits-017 Clamping Circuit-Upward Shift

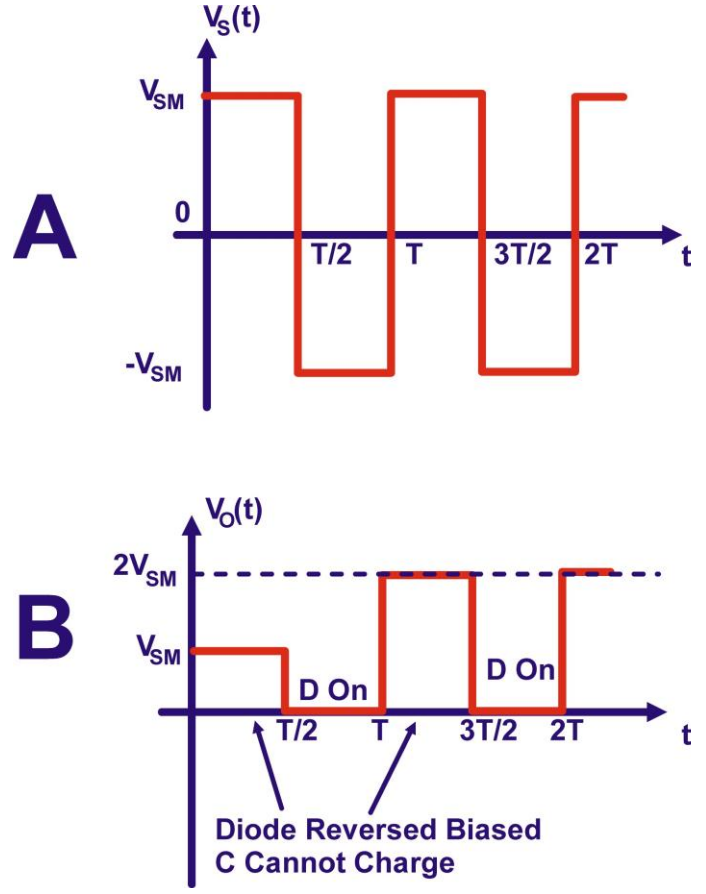

Figure 18, Diode-Circuits-018 Clamping Circuit-Upward Shift

k. During the positive half -cycle of the input waveform, the diode is reverse biased and the capacitor cannot charge through R due to its large time constant. Thus, the capacitor voltage stays basically at zero. Hence, the output voltage is the same as the input voltage.

l. During the negative half -cycle, the diode is forward biased. For an ideal diode, the capacitor charges to its maximum value of V_{sm} with the polarity as shown. The output voltage is zero as the ideal diode is now conducting.

m. During the next positive half-cycle, the diode is reverse biased again. The output voltage is algebraic sum of the voltage across the capacitor and the input voltage. During this cycle, the capacitor cannot discharge owing to its large time constant again. From now onward, the capacitor voltage stays at V_{sm} with the polarity as shown in the figure. Thus, the capacitor behaves like a constant voltage source whose value is equal to the maximum value of the input voltage source for an ideal diode in the circuit.

n. The input and the output voltage waveforms are given in Figure "Diode-Circuits-018". Note that the output voltage has shifted up, its minimum value is zero, and the maximum value is $2V_{sm}$. Once again, note that the shift is in the direct ion of the arrow of the diode. Since there is no voltage source in series with the diode, the minimum output voltage under deal condition is zero.

o. Consider the circuit given in Figure "Diode-Circuits-019"-A, where the capacitor is initially uncharged and the input voltage is given in Figure "Diode-Circuits-020"-A.

p. As the input voltage jumps to its high value of 3 V, the ideal diode is forward biased and the corresponding circuit is given in Figure "Diode-Circuits-019"-B. The capacitor immediately charges up to 2 V with the polarity as indicated in Figure "Diode-Circuits-020"-B, and the output voltage is 1 V in accordance with the ideal-diode assumption. The capacitor remains charged until the input voltage reverses its polarity.

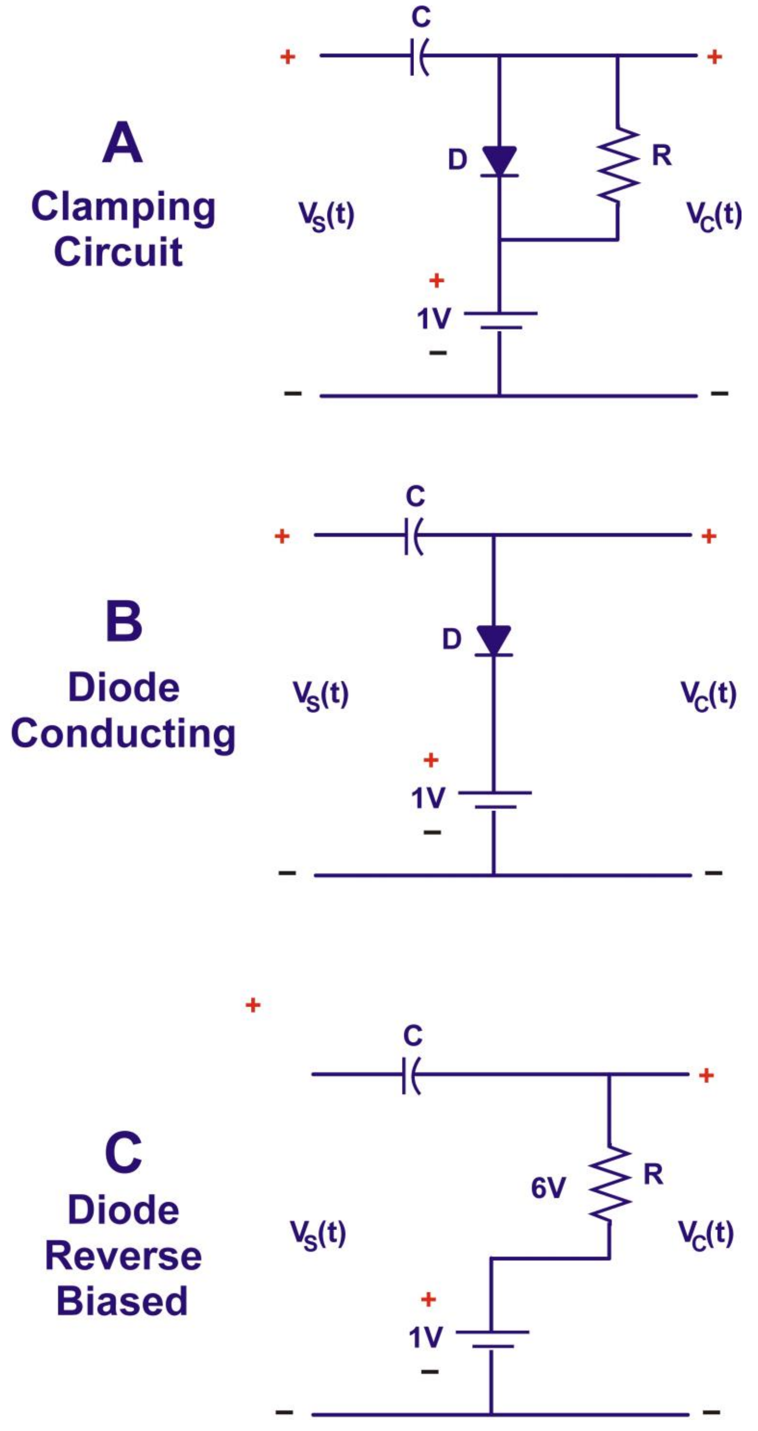

Figure 19, Diode-Circuits-019 Second Diode Clamping Circuit

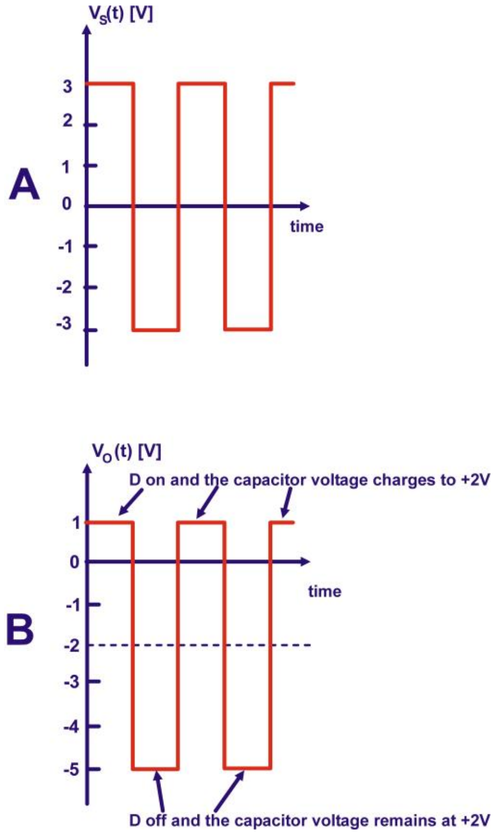

Figure 20, Diode-Circuits-020 Second Diode Clamping Circuit Graphs

q. When the input voltage becomes negative (–3V), the diode is reverse biased as shown in Figure "Diode-Circuits-019"-C. The current completes its path through the resistor. If the time constant (RC) is very large, the capacitor voltage basically remains unaffected and there is a 6 V drop across R with the polarity as shown in the figure. Thus, the output voltage is –5V.

7. Diode Clippers

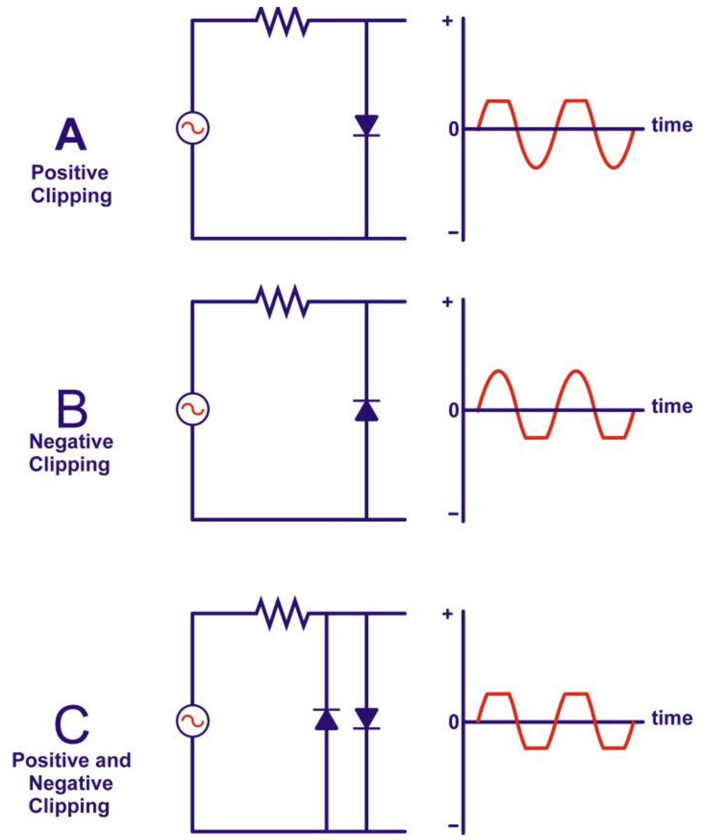

Figure 21, Diode-Circuits-021 Diode Limiting (Clipper) Circuits

a. Limiting circuits limit, or clip, the input signal such that the output signal will not exceed the limiting voltage.

b. In Figure "Diode-Circuits-021"-A, a positive limiter (clipper) is shown. Within the operating parameters of the circuit components, the output voltage will not go higher than the forward biasing voltage drop across the diode.

c. In Figure "Diode-Circuits-021"-B, a negative limiter (clipper) is shown. Within the operating parameters of the circuit components, the output voltage will not go lower than the forward biasing voltage drop across the diode.

d. In Figure "Diode-Circuits-021"-C, a positive and negative limiter (clipper) is shown. Within the operating parameters of the circuit components, the output voltage will not go above or below the forward biasing voltage drop across the diodes.

e. Depending on the materials from which the diodes are constructed, the forward biasing voltage drop of a diode ranges from 0.5V to 0.7 volts.

f. To have different limiting (clipping) values, zener diodes may be used.

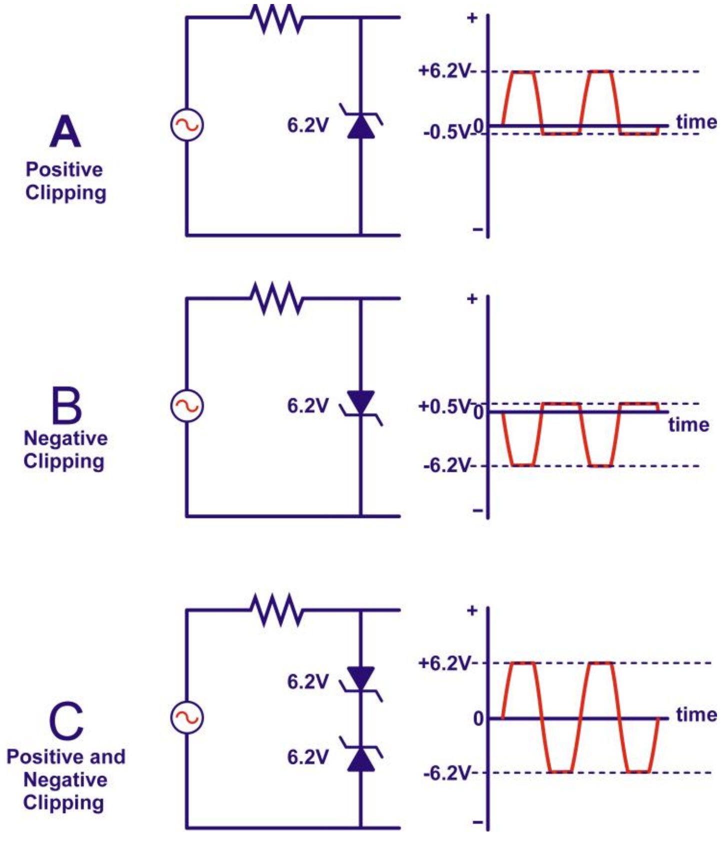

Figure 22, Diode-Circuits-022 Zener Diode Limiting (Clipper) Circuits

g. In Figure "Diode-Circuits-022"-A &-B, when the Zener diode is forward biased, the voltage across the diode will be no more than about 0.5 V. When the diode is reverse biased, the voltage drop across the diode will be no more that the zener breakdown voltage (in this case 6.2 volts.)

h. In "Diode-Circuits-022" -C, the voltage drop across both diodes will be the reverse bias breakdown voltage of one diode added to the forward bias voltage drop of the other diode, in this case 6.2V + 0.5V for a total of 6.7 volts.

8. Zener Voltage Regulator

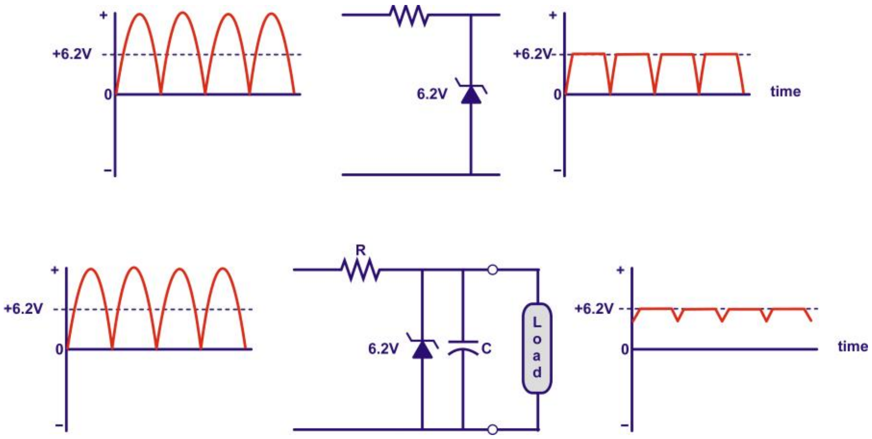

Figure 23, Diode-Circuits-023 Zener Diode Regulator Circuit

a. In Figure "Diode-Circuits-023" (top), the input signal is a full-wave rectified voltage from an AC source. The signal level does not go below zero. The zener clips the voltage at the reverse bias breakdown voltage (6.2V).

b. In Figure "Diode-Circuits-023" (bottom), a capacitor is added across the diode. Depending on the load resistance, the value of R, the value of C, and the current capabilities of the source voltage, the voltage across the load will approach a constant (straight line, no ripple) voltage.