

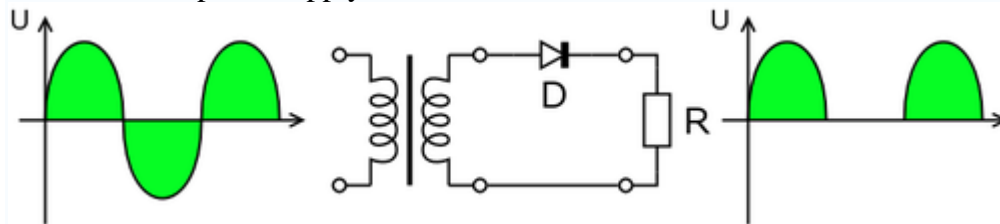
ELECTRONIC CONTROL

The three components of an electronic controller are a rectifier from ac to dc, a dc control section, and an inverter to convert dc to ac. This obviously involves both a level and a frequency.

RECTIFICATION

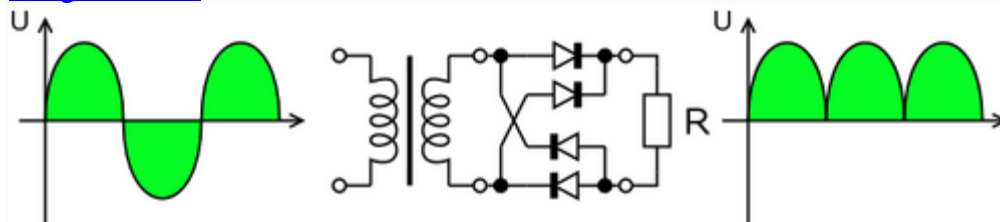
Half-wave rectification

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.

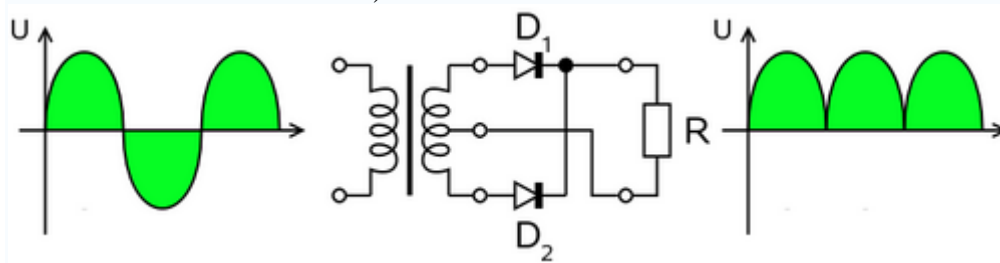


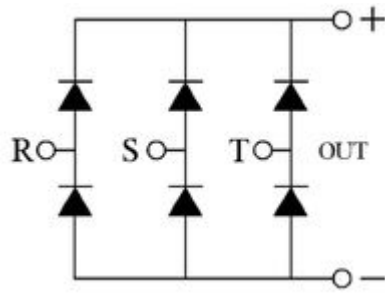
Full-wave rectification

Full-wave rectification converts both polarities of the input waveform to DC, and is more efficient. However, in a circuit with a non-[center tapped](#) transformer, four rectifiers are required instead of the one needed for half-wave rectification. This is due to each output polarity requiring 2 rectifiers each, for example, one for when AC terminal 'X' is positive and one for when AC terminal 'Y' is positive. The other DC output requires exactly the same, resulting in four individual junctions (See semiconductors/diode). Four rectifiers arranged this way are called a [bridge rectifier](#):



A full wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output by reversing the negative (or positive) portions of the alternating current waveform. The positive (negative) portions thus combine with the reversed negative (positive) portions to produce an entirely positive(negative) voltage/current waveform. For single phase AC, if the AC is center-tapped, then two diodes back-to-back (i.e. anodes-to-anode or cathode-to-cathode) form a full wave rectifier.





Three Phase Bridge Rectifier.

For three phase AC, six diodes are used. Typically there are three pairs of diodes, each pair, though, is not the same kind of **double diode** that would be used for a full wave single phase rectifier. Instead the pairs are in series ([anode](#) to [cathode](#)). Typically, commercially available double diodes have four terminals so the user can configure them as single phase split supply use, for half a bridge, or for three phase use.



Disassembled automobile alternator, showing the six diodes that comprise a full-wave three phase bridge rectifier.

Most devices that generate alternating current (such devices are called [alternators](#)) generate three phase AC. For example, an automobile alternator has six diodes inside it to function as a full wave rectifier for battery charge applications.

Peak loss

An aspect of most rectification is a loss from peak input voltage to the peak output voltage, caused by the threshold voltage of the diodes (around 0.7 V for ordinary diodes and 0.1 V for [Schottky diodes](#)). Half wave rectification and full wave rectification using two separate secondaries will have a peak voltage loss of one diode drop. Bridge rectification will have a loss of two diode drops. This may represent significant power loss in very low voltage supplies. In addition, the diodes will not conduct below this voltage, so the circuit is only passing current through for a portion of each half-cycle, causing short segments of zero voltage to appear between each "hump".

Rectifier output smoothing

While half- and full-wave rectification suffices to deliver a *form* of DC output, neither produces constant voltage DC. In order to produce *steady* DC from a rectified AC supply, a **smoothing** circuit is required. In its simplest form this can be what is known as a [reservoir capacitor](#) or smoothing capacitor, placed at the DC output of the rectifier. There will still remain an amount of AC [ripple](#) voltage where the voltage is not completely smoothed.

Sizing of the capacitor represents a tradeoff. For a given load, a larger capacitor will reduce ripple but will cost more and will create higher peak currents in the transformer secondary and in the supply feeding it. In extreme cases where many rectifiers are loaded onto a power distribution circuit, it may prove difficult for the power distribution authority to maintain a correctly shaped sinusoidal voltage curve.

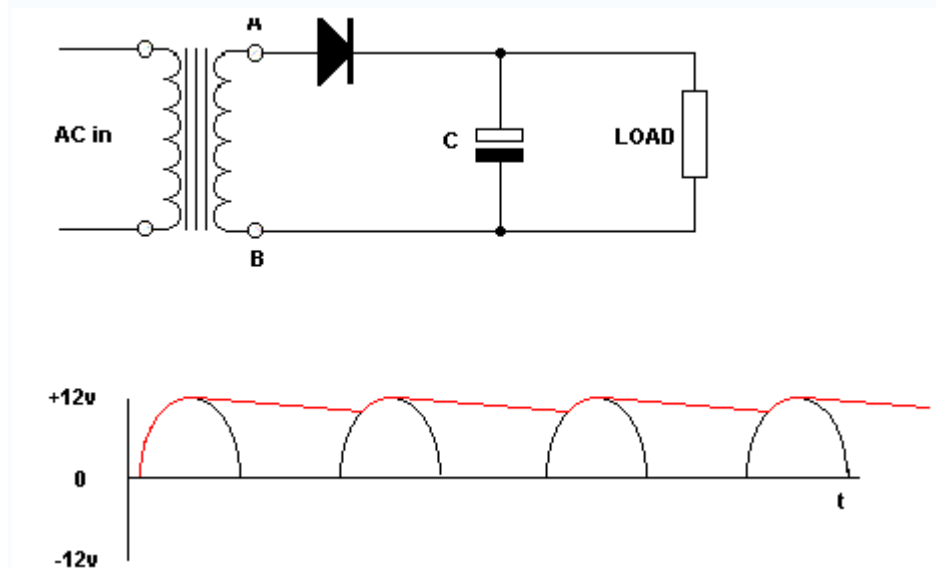
Three phase bridges provide six peaks per cycle rather than two meaning the capacitor size can be significantly reduced if a 3 phase supply is available.

To further reduce this ripple, a [capacitor-input filter](#) can be used. This complements the reservoir capacitor with a [choke](#) and a second [filter capacitor](#), so that a steadier DC output can be obtained across the terminals of the filter capacitor. The choke presents a high [impedance](#) to the ripple current.

If the DC load is very demanding of a smooth supply voltage, a [voltage regulator](#) will be used either instead of or in addition to the capacitor-input filter, both to remove the last of the ripple and to deal with variations in supply and load characteristics.

Reservoir capacitor

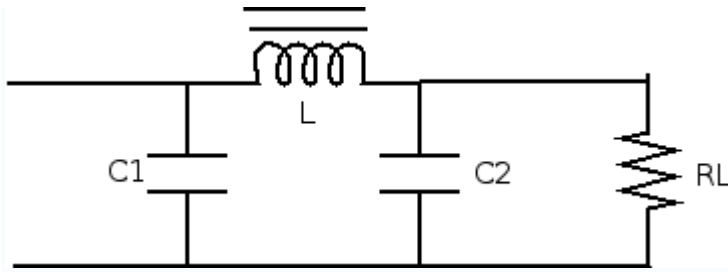
The pulsating DC from an AC rectifier (either half-wave or full-wave) sometimes needs to be smoothed to be useful. This can be done using a Reservoir capacitor.



As the rectifier voltage increases, it charges the capacitor and also supplies current to the load. At the end of the quarter cycle the capacitor is charged to its peak value V_m of the rectifier voltage. Following this the rectifier voltage starts to decrease as it enters the next quarter cycle. This initiates the discharge of the capacitor through the load.

Capacitor-input filter

The capacitor-input filter is a type of filter circuit. Filter circuits are used to remove the AC component from the rectified output and allows only the DC component to reach the load.

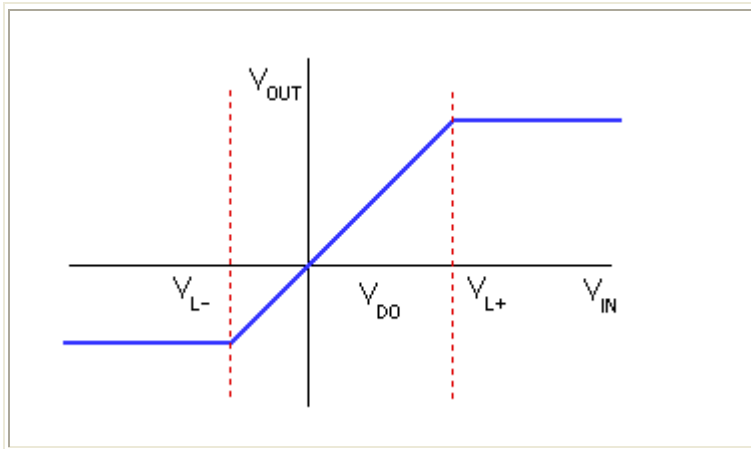


A typical capacitor input filter consists of a filter capacitor C1, connected across the rectifier output, a choke L, in series and another filter capacitor connected across the load.

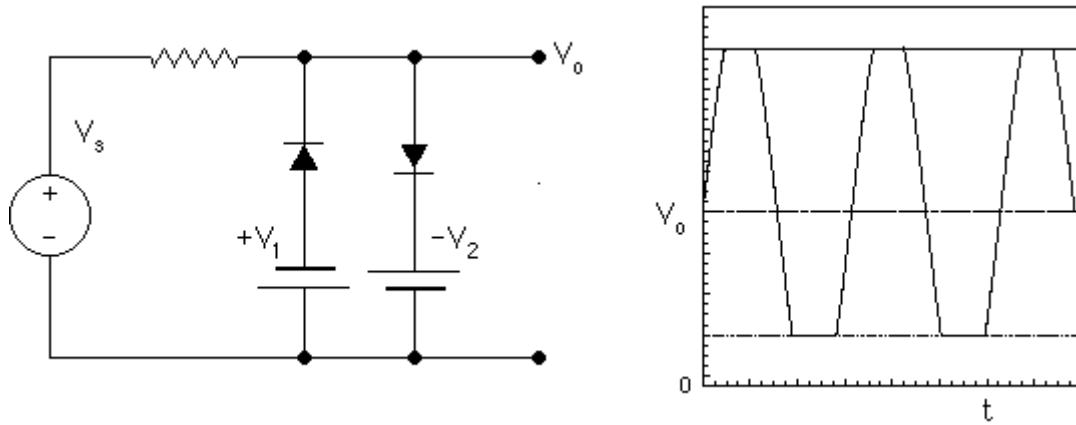
1. The capacitor C1 offers low reactance to the AC component of the rectifier output while it offers infinite reactance to the DC component. As a result the capacitor bypasses an appreciable amount of the AC component while the DC component continues its journey to the choke L
2. The [choke](#) L offers high reactance to the AC component but it offers almost zero reactance to the DC component. As a result the DC component flows through the choke while the AC component is blocked.
3. The capacitor C2 bypasses the AC component which the choke had failed to block. As a result only the DC component appears across the load.

SMOOTHING

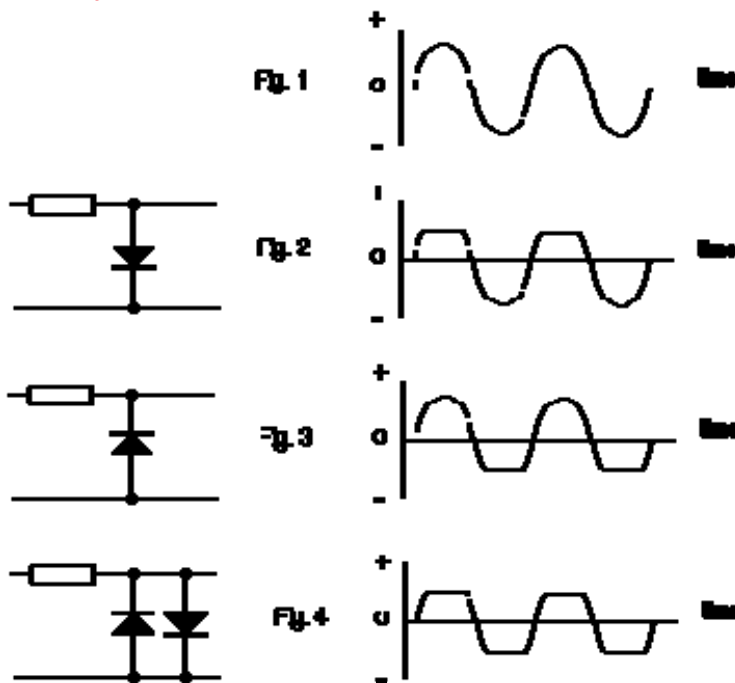
Clippers/Limiters



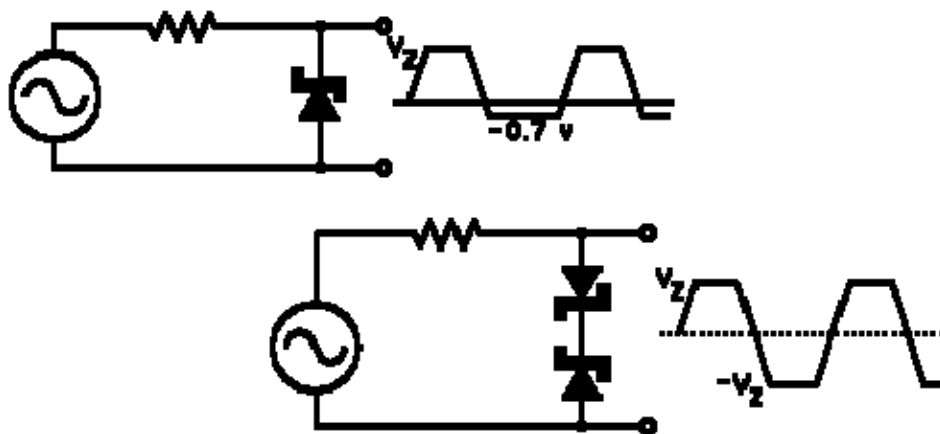
"A diode clipping circuit can be used to limit the voltage swing of a signal. Figure Ö shows a diode circuit that clips both the positive and negative voltage swings to reference voltages."



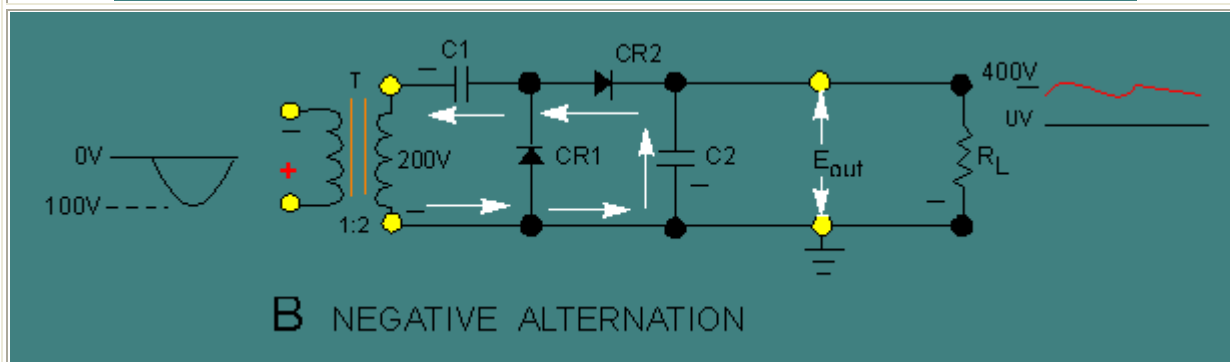
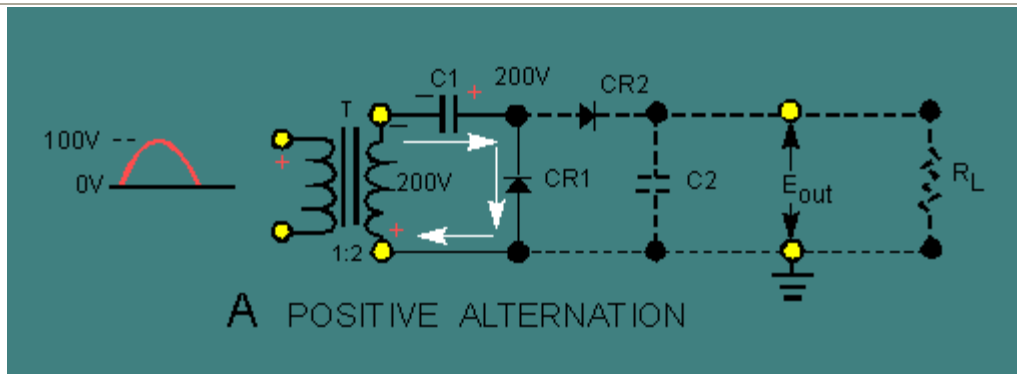
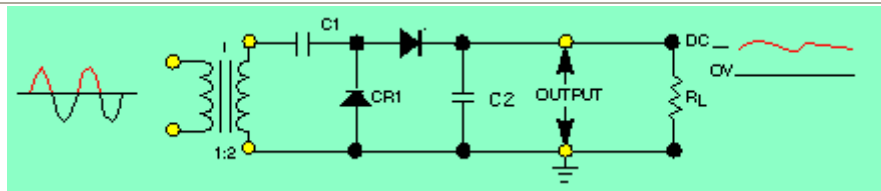
Limiting with ordinary diodes:



Limiting with Zener diodes:

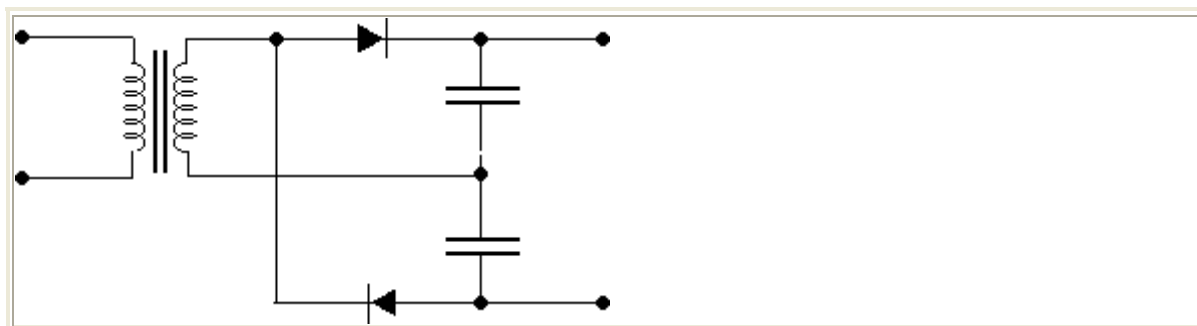


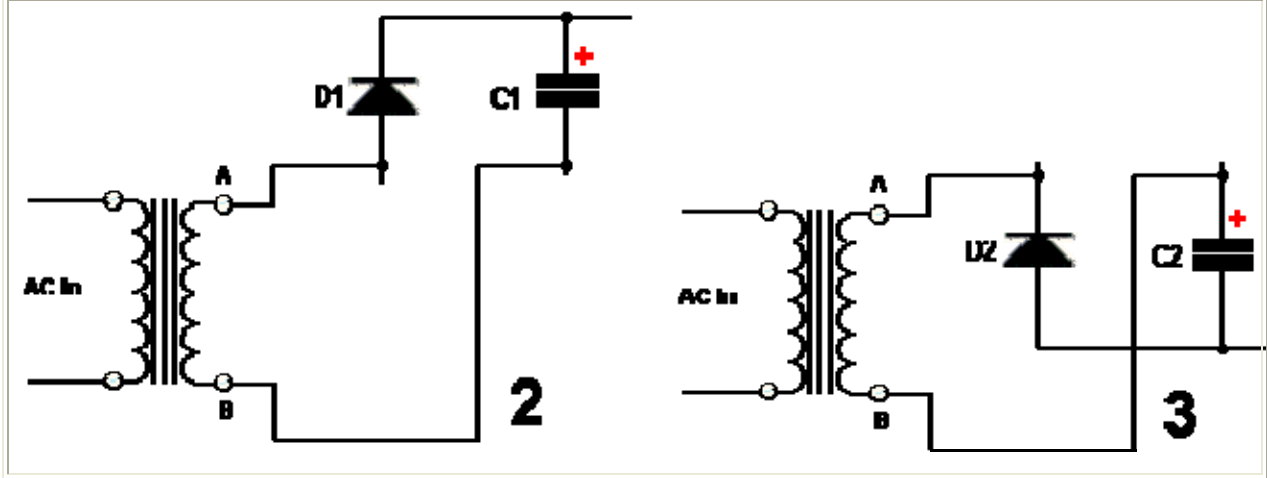
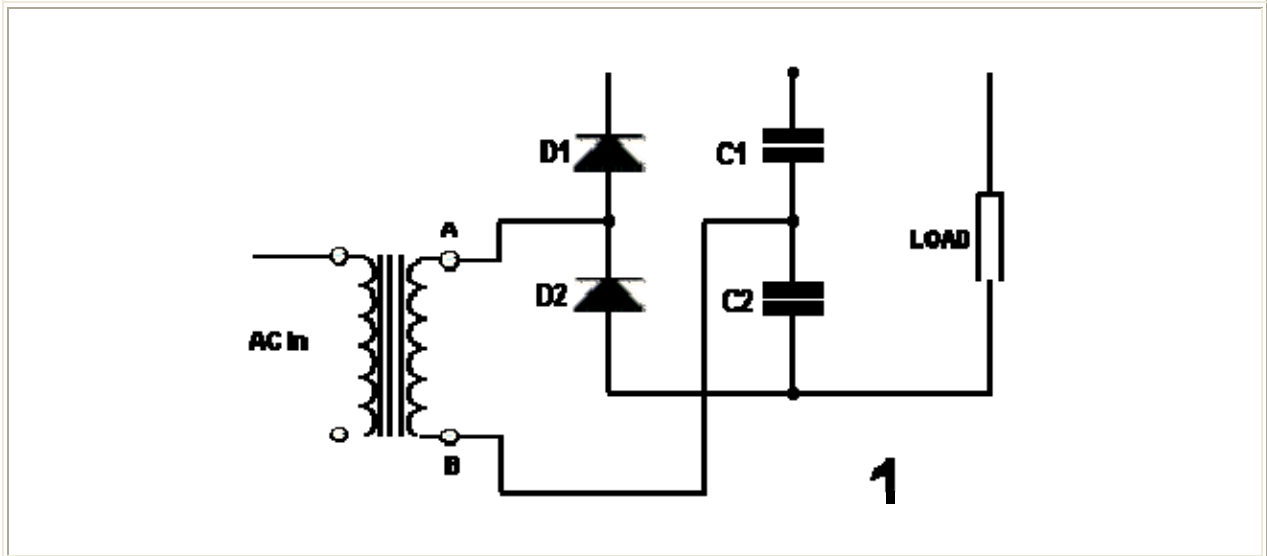
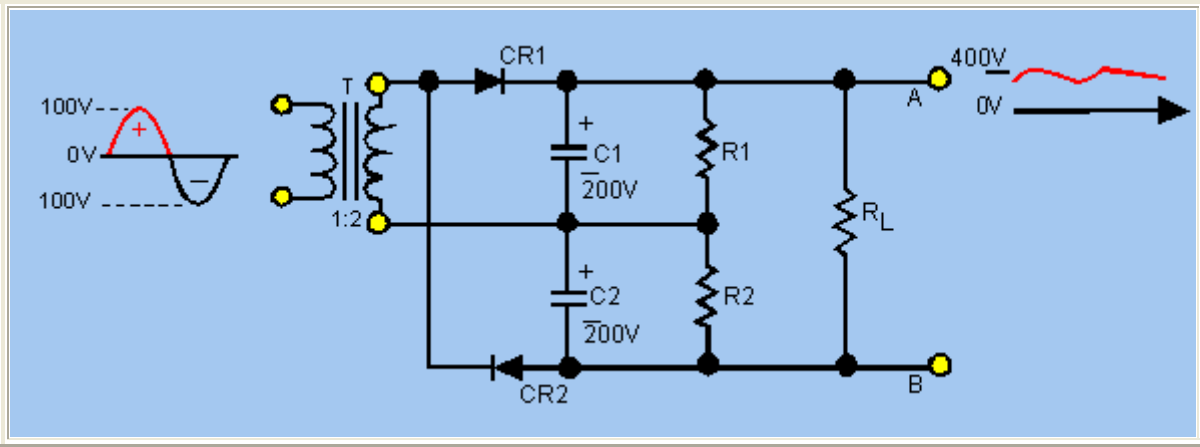
- Doubler - A dc restorer followed by a peak detector



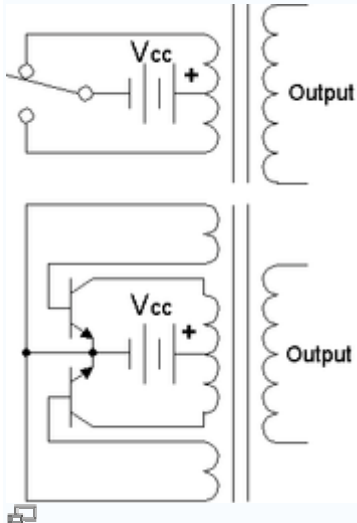
Doubler – Another approach

"A voltage multiplier circuit is shown in figure. We can think of it as two half-wave rectifier circuits in series. During the positive half-cycle one of the diodes conducts and charges a capacitor. During the negative half-cycle the other diode conducts negatively to charge the other capacitor. The voltage across the combination is therefore equal to twice the peak voltage. In this type of circuit we have to assume that the load does not draw a significant charge from the capacitors."





INVERTER CIRCUIT DESCRIPTION



Simple inverter circuit shown with an electromechanical switch and with a transistor switch

Basic inverter designs

In one simple inverter circuit, DC power is connected to a [transformer](#) through the center tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces [alternating current](#) (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a [vibrator](#) or buzzer, was once used in [vacuum tubes](#) automobile radios. A similar mechanism has been used in door bells, buzzers and [tattoo guns](#).

These electromechanical inverters explain the source of the term "inverter". Early AC to DC converters combined a synchronous AC motor with a commutator so that the commutator reversed its connections to the AC line exactly twice per cycle. This results in AC-in, DC-out. If you invert the connections to a converter you put DC in and get AC out. Hence an inverter is an inverted converter. [1]

As they became available, [transistors](#) and various other types of [semiconductor](#) switches have been incorporated into inverter circuit designs.

More advanced inverter designs

In more advanced inverter designs various techniques are used to improve the quality of the [sine wave](#) at the transformer input, rather than relying on the transformer to smooth it. [Capacitors](#) and [inductors](#) (but not [freewheel diode](#) as it is AC) can be used to filter the waveform at the primary of the transformer. Also, it is possible to produce a more sinusoidal wave by having split-rail [direct current](#) inputs at two voltages, or positive and negative inputs with a central [ground](#). By connecting the transformer input terminals in sequence between the positive rail and ground, the positive rail and the negative rail, the ground rail and the negative rail, then both to the ground rail, a stepped sinusoid is generated at the transformer input and the current drain on the [direct current](#) supply is less choppy. These methods result in an output that is called a "modified-sine wave". Modified-sine inverters may cause some loads, such as motors, to operate less efficiently.

More expensive power inverters use Pulse Width Modulation ([PWM](#)) with a high frequency carrier to more closely approximate a sine function. The quality of an inverter is described by its pulse-rating: a 3-pulse is a very simple arrangement, utilising only 3 transistors, whereas a more complex 12-pulse system will give an almost exact sine wave. In remote areas where a utility generated power is subject to significant external, distorting influences such as inductive loads or semiconductor-rectifier loads, a 12-pulse inverter may even offer a better, "cleaner" output than the utility-supplied power grid, and are thus often used in these areas. Inverters with greater pulse ratings do exist.

Simple inverters generate harmonics which affect the quality of power obtained using them. But PWM inverters eliminate this by means of a sine wave cancellation using the properties of Fourier Series.

Inverter applications

The following are examples of inverter applications.

DC power source utilization



Inverter designed to provide 115 VAC from the 12 VDC source provided in an automobile

An inverter allows the 12 volt DC power available in an automobile to supply AC power to operate equipment that is normally supplied from a mains power source.

Inverters are also used to provide a source of AC power from [solar cell](#) and [fuel cell](#) power supplies.



Uninterruptible power supplies

One type of [uninterruptible power supply](#) uses batteries to store power and an inverter to supply AC power from the batteries when mains power is not available. When mains power is restored, a rectifier is used to supply DC power to recharge the batteries.

Induction heating

Inverters are used to convert low frequency mains AC power to a higher frequency for use in [induction heating](#). To do this, AC power is first [rectified](#) to provide DC power. The inverter then changes the DC power to high frequency AC power.

High-voltage direct current (HVDC) power transmission

With [HVDC](#) power transmission, AC power is rectified and high voltage DC power is transmitted to another location. At the receiving location, an inverter in a [static inverter plant](#) converts the power back to AC.

Variable frequency drives

A [variable frequency drive](#) controls the operating speed of an AC motor by controlling the frequency and voltage of the power supplied to the motor. An inverter provides the controlled power. In most cases, the variable frequency drive includes a [rectifier](#) so that DC power for the inverter can be provided from mains AC power. Since an inverter is the key component, variable frequency drives are sometimes called inverter drives or just inverters.

Variable frequency drive

A **Variable Frequency Drive** (sometimes abbreviated **VFD**) is a system for controlling the rotational speed of an [alternating current](#) (AC) [electric motor](#) by controlling the frequency of the electrical power supplied to the motor. A variable frequency drive is a specific type of [adjustable speed drive](#). Variable frequency drives are also known as adjustable frequency drives (AFD), variable speed drives (VSD), AC drives or inverter drives.



Operating principle

Variable frequency drives operate under the principle that the synchronous speed of an AC motor is determined by the frequency of the AC supply and the number of poles in the stator winding, according to the relation:

$$RPM = \frac{120 \times f}{p}$$

where

RPM = Revolutions per minute

f = AC power frequency (Hertz)

p = Number of poles (an even number)

Synchronous motors operate at the synchronous speed determined by the above equation. The speed of an induction motor is slightly less than the synchronous speed.

Example

A 4-pole motor that is connected directly to 60 Hz utility (mains) power would have a synchronous speed of 1800 RPM:

$$\frac{120 \times 60}{4} = 1800 RPM$$

If the motor is an induction motor, the operating speed at full load will be about 1750 RPM.

If the motor is connected to a speed controller that provides power at 40 Hz, the synchronous speed would be 1200 RPM:

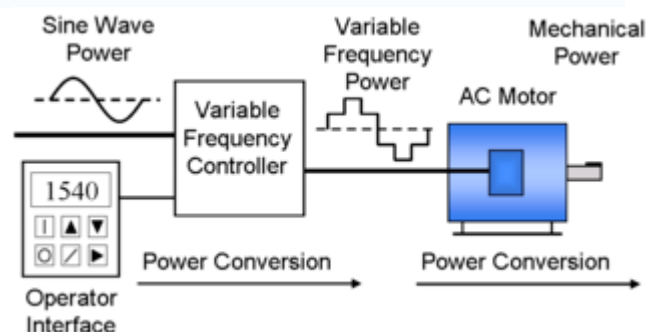
$$\frac{120 \times 40}{4} = 1200 RPM$$

VF Description

A variable frequency drive system generally consists of an AC motor, a controller and an operator interface.

VFD Motor

The motor used in a VFD system is usually a [three-phase](#) induction motor. Some types of [single-phase](#) motors can be used, but three-phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations, but induction motors are suitable for most purposes and are generally the most economical choice. Motors that are designed for fixed-

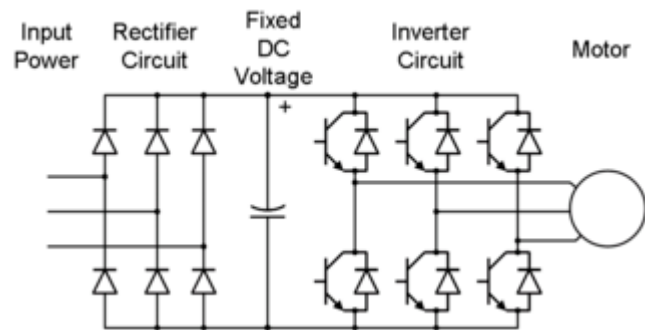


speed mains voltage operation are often used, but certain enhancements to the standard motor designs offer higher reliability and better VFD performance.

VFD Controller

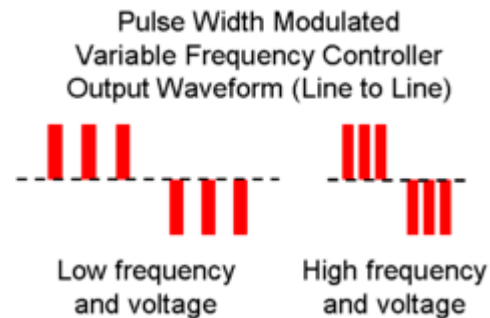
Variable frequency drive controllers are [solid state electronic](#) power conversion devices. The usual design first converts AC input power to DC intermediate power using a [rectifier](#) bridge. The DC intermediate power is then converted to quasi-sinusoidal AC power using an inverter switching circuit. The rectifier is usually a three-phase diode bridge, but controlled rectifier circuits are also used. Since incoming power is converted to DC, many units will accept single-phase as well as three-phase input power (acting as a phase converter as well as a speed controller); however the unit must be derated when using single phase input as only part of the rectifier bridge is carrying the connected load.

As new types of [semiconductor](#) switches have been introduced, they have promptly been applied to inverter circuits at all voltage and current ratings for which suitable devices are available. Currently, insulated gate bipolar transistors ([IGBTs](#)) are used in most VFD inverter circuits.



AC motor characteristics require the applied voltage to be proportionally adjusted whenever the frequency is changed. For example, if a motor is designed to operate at 460 volts at 60 Hz, the applied voltage must be reduced to 230 volts when the frequency is reduced to 30 Hz. Thus the ratio of volts per hertz must be regulated to a constant value ($460/60 = 7.67$ in this case). For optimum performance, some further voltage adjustment may be necessary, but nominally constant volts per hertz is the general rule. The latest method used for adjusting the motor voltage is called pulse width modulation PWM. With PWM voltage control, the inverter switches are used to divide the quasi-sinusoidal output waveform into a series of narrow voltage pulses and modulate the width of the pulses.

 PWM VFD Output Voltage Waveform



An [embedded microprocessor](#) governs the overall operation of the VFD controller. The main microprocessor programming is in [firmware](#) that is inaccessible to the VFD user. However, some degree of configuration programming and parameter adjustment is usually provided so that the user can customize the VFD controller to suit specific motor and driven equipment requirements.

VFD Operator interface

The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed. Additional operator control functions might include reversing and switching between manual speed adjustment and automatic control from an external [process control](#) signal. The operator interface often includes an [alphanumeric](#) display and/or indication lights and meters to provide information about the operation of the drive. An operator interface keypad and display unit is often provided on the front of the VFD controller as shown in the photograph above. The keypad display can often be cable-connected and mounted a short distance from the VFD controller. Most are also provided with [input and output](#) (I/O) terminals for connecting pushbuttons, switches and other operator interface devices or control signals. A [serial](#)

[communications port](#) is also often available to allow the VFD to be configured, adjusted, monitored and controlled using a computer.

VFD Operation

When a VFD starts a motor, it initially applies a low frequency and voltage to the motor. The starting frequency is typically 2 Hz or less. Starting at such a low frequency avoids the high inrush current that occurs when a motor is started by simply applying the utility (mains) voltage by turning on a switch. When a VFD starts, the applied frequency and voltage are increased at a controlled rate or ramped up to [accelerate](#) the load without drawing excessive current. This starting method typically allows a motor to develop 150% of its rated [torque](#) while drawing only 150% of its rated current. When a motor is simply switched on at full voltage, it initially draws at least 300% of its rated current while producing less than 150% of its rated torque. As the load accelerates, the available torque usually drops a little and then rises to a peak while the current remains very high until the motor approaches full speed. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed while drawing only 150% current.

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help [decelerate](#) the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit to dissipate the braking energy or return it to the power source.

Available VFD power ratings

Variable frequency drives are available with voltage and current ratings to match the majority of 3-phase motors that are manufactured for operation from utility (mains) power. VFD controllers designed to operate at 110 volts to 690 volts are often classified as low voltage units. Low voltage units are typically designed for use with motors rated to deliver 0.2kW or 1/4 [horsepower](#) (Hp) up to at least 750kW or 1000Hp. Medium voltage VFD controllers are designed to operate at 2400/4160 volts(60Hz), 3300 volts(50Hz) or up to 10kV. In some applications a step up [Transformer](#) is placed between a low voltage drive and a medium voltage load. Medium voltage units are typically designed for use with motors rated to deliver 375kW or 500Hp and above. Medium voltage drives rated above 7kV and 5000 or 10,000Hp should probably be considered to be one-of-a-kind (one-off) designs.