Introduction to DC Power Supplies

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Introduction

The type of DC power supply discussed here concerns one that derives is operating energy from the AC power line via an isolated winding on a transformer. The basic components of a DC power supply are:

1. Power Transformer

2. Rectifier

3. Filter (usually a capacitor)

4. Voltage Regulator

Each component is discussed in the following sections. The purpose of this introduction is to explain a variety of concepts with only minimum mathematics.

Power Transformer

The power transformer provides separate windings to isolate the primary and secondary circuits. Isolation is necessary for safety considerations. Bizarre accidents are possible with non-isolated systems. An autotransformer with shared windings is insufficient. The two windings must be electrically isolated.

A transformer also provides line voltage step down or up as needed by the DC power supply. Most electronics operates at voltages well below the power line voltage so the discussion will focus on step down. Using a transformer, voltages can be transformed from one level to another with minimum power loss.

All transformers have a voltage rating, frequency rating, and volt-ampere rating. The voltage rating is generally the nominal line voltage the transformer is designed to operate with. As an example, a nominal 120 Vrms primary is intended to operate with nominal 120 Vrms line voltage but the nominal range might vary from less than 110 volts up to over 125 volts. There is a maximum line voltage (although that data is usually hard to find in the specifications) at which the core begins to saturate appreciably resulting in increased power losses – i.e. heat. A 120 volt transformer would be destroyed very quickly if connected to 240 volts.

All transformers have a volt-ampere rating which is the maximum power (real or imaginary) that the secondary can deliver to a load. This rating is a function of the physical size of the iron core. Ideally, the load is resistive and the volt-ampere rating then represents the power in watts. However, the input impedance to the rectifier and filter of a power supply is significantly reactive and non-linear and the actual maximum DC power that can be extracted is much lower than the volt-ampere rating of the transformer. That is referred to as transformer utilization. The transformer utilization factor, TUF, is the maximum DC output power of the rectifier system divided by the transformer volt-ampere rating. It is always less than 1.0.

Note that the volt-ampere rating only applies when the transformer is operated at the specified line voltage. Under no conditions should the current in the windings exceed the maximum current rating of the transformer or else the core will saturate resulting is significant power loss – i.e. heat. Thus, a 120 volt transformer with a 10 volt secondary that can source 8 amperes (i.e. the volt-ampere rating of the transformer is 80) can still only source 8 amperes into a 5 volt load if the primary voltage were halved.

A power transformer design is only optimum for a small range of frequencies. A transformer designed for 60 Hz operation will generally not work at 50 Hz at full line voltage – the core will saturate causing high losses and the transformer will over heat as it draws high line current even if unloaded. However, a transformer designed for 50 Hz will work at 60 Hz with no problem. Such transformers are often referred to as 50/60 Hz.

Transformers are generally designed so that the core losses are similar in magnitude to the ohmic losses in the windings as that tends to minimize the total loss. A large number of turns can be used to minimize core losses but then ohmic losses increase because of the long length of fine wire. Alternatively a small number of turns of large wire can be used to minimize ohmic losses but then core losses are high.

A transformer should never be loaded to its source impedance – that would generally destroy the transformer. The maximum power transfer theorem does not apply because the transformer is a non-linear device. A transformer should only be loaded up to its maximum ratings.

The efficiency of large power transformers (over a few hundred volt-ampere rating) is typically in the ninety percent range. However, small power transformers in the few tens of volt-ampere ratings generally are only about seventy percent efficient or less as it is not practical or cost effective to manufacture those at high efficiencies.

The optimum winding configuration is for the primary winding(s) to occupy half of the available winding volume. The number of turns on the secondary winding(s) are then determined by the turns ratio needed for the particular voltage but increased somewhat to allow for transformer losses. As an example, a 12 volt secondary would theoretically need a 10:1 turns ratio for operation on a 120 VAC power line but the real turns ratio required will likely turn out to be closer to 9:1 or perhaps as low as 7:1. The allowance factor generally has to be determined experimentally as there are too many complicating and not well known factors to directly calculate. The no-load secondary voltage is typically at least ten but may be over thirty percent higher than the rated loaded voltage. That is an important point as the unloaded output voltage can be surprisingly high.

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It is very common for a power supply transformer to have two identical primary windings, each specified for 120 VAC, that can be connected in series aiding for operation on 240 VAC circuits or parallel aiding for operation on 120 VAC circuits. The operative word in each case is “aiding.” There will be a huge and destructive current if the windings are connected in phase opposition to each other. For 120 VAC operation it is important that both primaries be connected in parallel. Connecting only a single winding will result in significantly higher losses. Such transformers typically have dual secondary windings that can be connected in parallel for low voltage, high current or in series for high voltage, low current applications. Figure 1 shows an example.

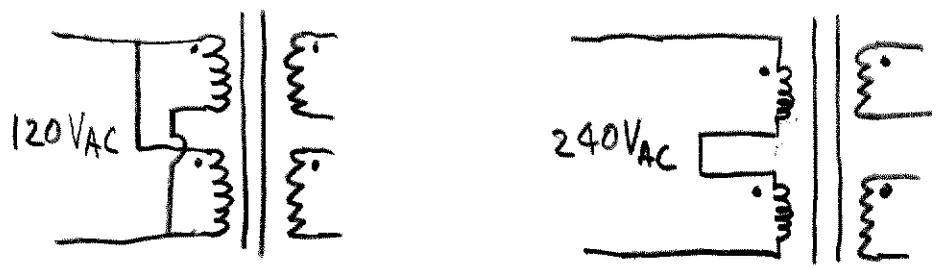

Figure 1: Power Transformer Primary Connections

Rectifiers

The rectification process uses diodes to permit current from the transformer in one direction and block reverse current. The alternating current thus becomes unidirectional current known as DC. At this point the current is in pulses rather than being continuous and smooth. But there is only one direction of the current thus it is DC. There are three types of rectifier circuits; half-wave, full-wave center-tap, and full-wave bridge.

The half-wave rectifier is shown in Figure 2. This circuit is only used for relatively low power applications since it makes very inefficient use of the capabilities of the power transformer (very low TUF). The circuit also requires more than twice the filter capacitance than a full-wave type for the same amount of ripple voltage.

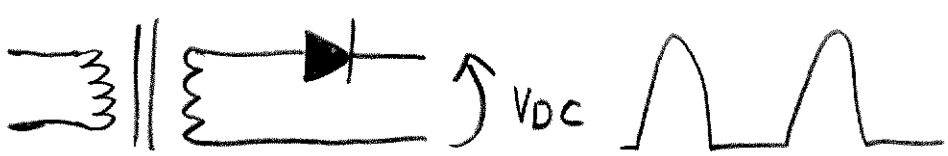

Figure 2: Half-wave rectifier

The full-wave center-tap rectifier shown in Figure 3 is essentially two half-wave rectifiers operating on alternate phases and combined. D1 conducts on one half cycle and D2 conducts on the other half cycle. This circuit is a significant improvement over the half-wave rectifier but still suffers from reduced utilization of the power transformer since each winding of the transformer is only used half the time.

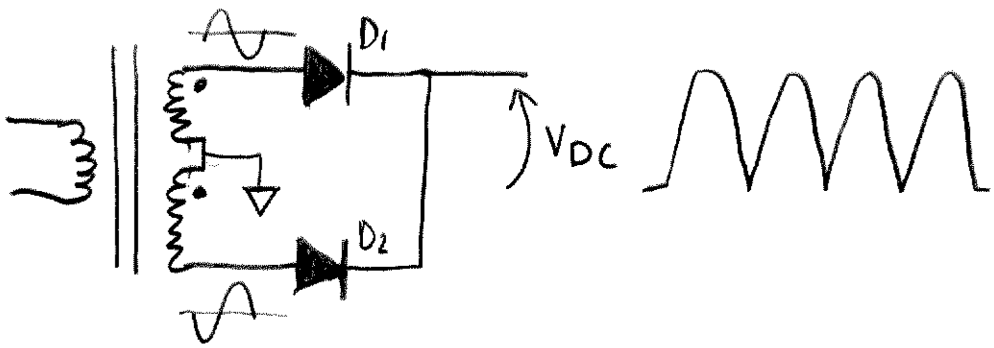

Figure 3: Full-wave center-tapped rectifier

Historically, the two diodes were of the vacuum tube type and were combined in a single tube with a filament that typically served as the common cathode. This type of rectifier was common because it was practical with available components at that time. The expense and complications of full-wave bridge rectifiers made that implementation rare. In modern times with solid state diodes the full-wave bridge circuit is preferred because it has the highest utilization of the power transformer. Although the full-wave center-tapped rectifier works reasonably well it is nearly always inferior to the full-wave bridge except at very low secondary voltages where diode losses become dominant.

The full-wave bridge rectifier shown in Figure 4 uses four diodes and makes as full use of the transformer as is possible. In one half-cycle the current is through D1 to the load (not shown) and back through D3 to the transformer. In the other half-cycle the current is through D2 to the load and back through D4 to the transformer.

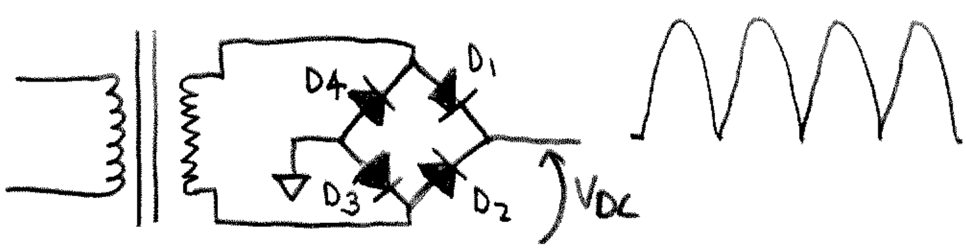

Figure 4: Full-wave bridge rectifier

Diodes manufactured for use as power rectifiers must be able to conduct high current pulses and are made physically large so that their bulk resistance is low. When conducting high currents the peak voltage drop across the junction is typically around 0.75 volts but the peak voltage drop across the internal bulk resistance may be over half a volt for a total drop of over 1.2 volts. Some important specifications for power diodes are as follows.

The **maximum average forward current** specification of the diode represents either a continuous current or effective value from pulsating currents.

The **maximum peak repetitive current** concerns the peak of the current pulses through the diode during each half cycle. This specification must not be exceeded even if the average forward current specification is met. This specification concerns continuous stress on the diode. Rectifiers with capacitor input filters have high peak currents since conduction through the diodes is only a brief part of the cycle. This peak current increases as the capacitance is increased for lower ripple voltage. It is possible to have too much filter capacitance thus leading to diode failure.

The **maximum peak surge current** specification applies when the power supply is turned on and the filter capacitor is not yet charged. To charge the capacitor the current through the rectifier diode will briefly be significantly higher than in normal operation. This is the most stressful part of the diode operation.

The **PIV (Peak Inverse Voltage)** is the maximum reverse voltage that the junction can withstand without breaking down.

There are more advanced specifications such as turn on time and turn off time that become increasingly important concerning power loss as the operating frequency is raised. These specifications are beyond the scope of this article. Always consult manufacturers' data sheets and application notes for important information concerning design.

Filter

Pulsating DC voltages are generally not useful for electronics. It is preferred to have a relatively constant DC voltage. The filter is frequently just a large capacitance to smooth the raw voltage fluctuations from the rectifier. More advanced designs will include a series inductor in addition to the capacitor for significantly improved filtering and also for improved efficiency in the rectification process. However, at low power line frequencies this is usually not practical except for high power applications because the required inductor is physically large. At high frequencies this approach is very practical. The capacitance required is typically ranges from a few hundred to many thousands of microfarads. It takes over twice as much capacitance for the same degree of smoothing for a half-wave rectifier compared to a full-wave rectifier.

The DC output voltage of the filter varies considerably with load current. For low current loads the voltage approaches the peak unloaded secondary voltage which for small power transformers can be around 1.2 * 1.414 * Vsecondary_rated. As an example the voltage across the capacitor using a 12 volt transformer will be in the vicinity of 20 volts. The fully loaded voltage might be in the vicinity of 10 volts.

The filter capacitance is usually of the electrolytic type in order to keep the physical size to a minimum. An electrolytic capacitor is made by sandwiching paper (or similar material) that has been soaked in an electrolyte between two strips of foil that serve as the two plates of the capacitor. When the capacitor is first made it is a low resistance as the electrolyte is conductive. To form the required insulation between the plates a controlled DC current is passed through the capacitor and an oxide layer forms on one of the plates over time and that thin layer becomes the insulation. Recall from the physics that capacitance is inversely proportional to the distance that separates the plates. Because the electrolyte is conductive except for the microscopically thin oxide layer the effective distance between the two plates is very small thus leading to a large capacitance in a small volume. However, the capacitor must never be exposed to a voltage polarity opposite to that which was used to form the oxide layer or else that layer will become conductive again. At that point the capacitor has failed and can become extremely hot and burst if there is nothing to limit the current. Thus, the filter capacitor will have a polarity marking and must be installed correctly.

The thin insulation between the two plates of the capacitor can only block a certain voltage. Thus, there is a maximum voltage that can exist across a capacitor. That voltage is known as the voltage rating and should be higher than the maximum voltage that would ever be across the capacitor. The engineer should consult with manufacturer's data to determine the appropriate voltage rating for a given application. A rough rule of thumb is to use a rating about 1.5 times the highest voltage. In years past that factor was an ultra-conservative value of two or three. Modern manufacturers typically discourage that practice as it can have detrimental effects on the performance of the capacitor. Always read, understand, and apply the manufacturers' application notes.

The plates and electrolyte are imperfect conductors and thus there is a resistance in series with the capacitor. This resistance is generally known as ESR (Effective Series Resistance) and a typical or maximum value is specified on the data sheet. The current through a filter capacitor typically consists of high amplitude pulses from the rectifier. Current through a resistance results in heat proportional to the current squared times the resistance. It is undesirable for the capacitor to heat as that damages the quality of the insulation and can ultimately dry out the electrolyte. Thus, capacitors have a ripple current rating that is usually given in rms at a ripple frequency of 120 Hz (twice the line frequency since full-wave rectification is assumed). The maximum ripple voltage specification is an alternative that is often easier to determine since voltage is directly measured. A common error is to overlook the ripple specifications of the capacitor. That can result in an insufficiently rated capacitor that will fail prematurely.

In addition to series resistance, a capacitor also has series inductance. This inductance forms a series resonant circuit typically in the thousands of Hz range. The net impedance of a capacitor increases with frequency above the series resonant point and the capacitor behaves as a lossy inductor. Where capacitance is needed over a wide frequency range it is common to see a parallel combination of a large capacitance with a smaller capacitance and perhaps with a still smaller capacitance. The result is lower impedance at higher frequencies because the series resonant frequency of smaller capacitances is higher than that for larger capacitances. However, complex interactions with the inductance of one capacitor with the capacitance of another can result in undesirable high parallel resonant impedances.

Figure 5 shows a full-wave bridge rectifier with filter capacitor. Note the use of the '+' sign on the capacitor to indicate proper polarity.

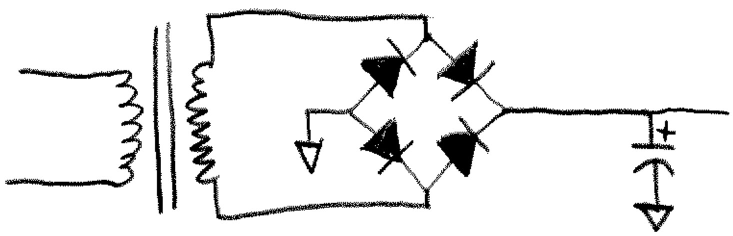

Figure 5: Full-wave bridge rectifier with filter capacitor

Voltage Regulator

The voltage regulator is typically a feedback control system that holds the regulated output voltage at a specific level. Voltage regulators can typically reduce the effect of input voltage variations and ripple by a factor of over one hundred to several thousand. The regulated output voltage is always less than the input voltage. However, the minimum input voltage (i.e. the minimum voltage level of the ripple voltage) must be above the regulated output voltage by at least several volts in order that the regulator can perform its job. Otherwise the output voltage will drop out of regulation. The average input voltage does not count – it is the minimum that is important. There are voltage regulators known as LDO (Low Drop Out) that can operate with a minimum input to output differential of less than two volts.

The most common type of voltage regulator is the three terminal integrated circuit fixed output voltage type. Some common voltages that these are available for include +5, +12, +15, -5, -12, and -15. The three terminals are for the unregulated input voltage, the regulated output voltage, and electrical ground. The power dissipated by the regulator includes a small amount for operation plus the dominate value of the input to output differential voltage multiplied by the load current. Since the power dissipated can be significant the package is designed for mounting to an appropriate heat sink. Figure 6 shows a typical simple power supply.

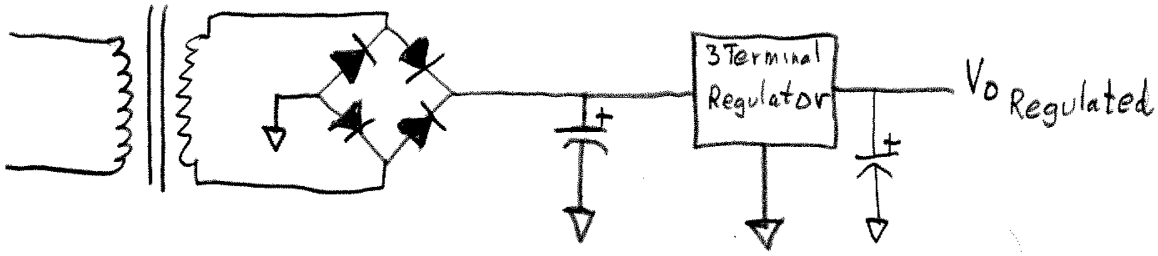

Figure 6: Simple power supply

Figure 7 shows a bipolar rectifier system. Note that the diode connections are the same as the previous bridge circuits but drawn differently. Essentially this circuit is a pair of full-wave center-tapped rectifiers, one for positive voltage and the other for negative voltage. This circuit is fairly common in simple power supplies.

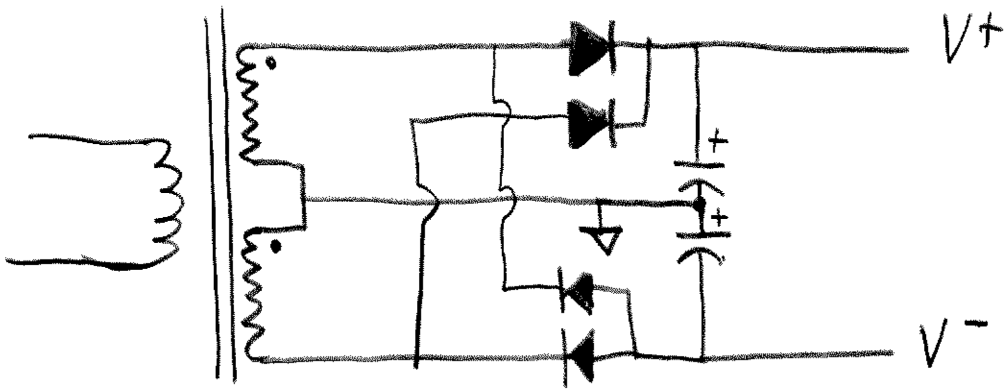

Figure 7: Bipolar rectifier

Figure 8 shows an alternative approach using a pair of full-wave bridge rectifiers, one for positive voltage and the other for negative voltage. Although it uses more diodes, the circuit may be less expensive to build under certain conditions since the required transformer may be smaller. The cost of a transformer is typically much higher than that of the diodes. Engineering for lowest cost does not always mean fewest total components.

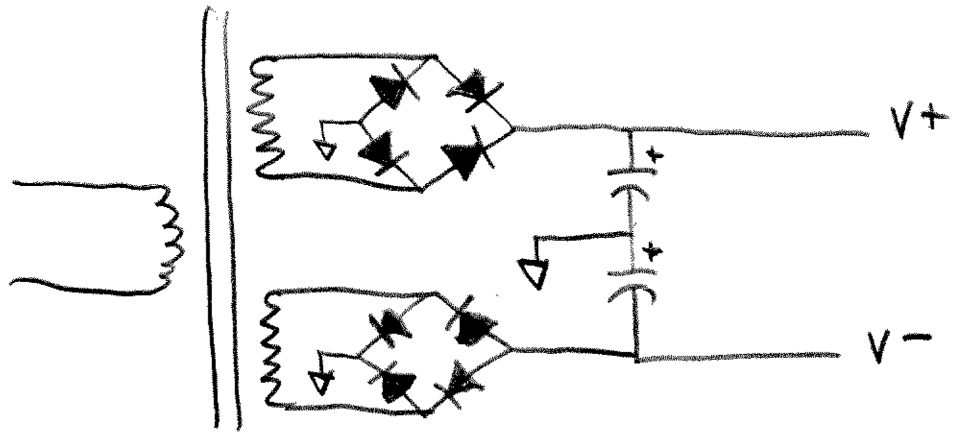

Figure 8: Bipolar rectifier using separate full-wave bridges

Physical Layout

It is important that the path from the transformer through the rectifiers and filter capacitor back to the transformer be of short length with high conductivity wires to minimize losses and also be of minimum loop area to minimize induction of the high current pulses into other circuits. Large loop area circuits cause induced interference problems that are practically impossible to solve short of rebuilding the power supply circuits properly.