Power Supplies

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Last updated on 2018-08-22 03:30:57 PM UTC

Guide Contents

Overview

What is a power supply?

A power supply is a device that **supplies power to another device, at a specific voltage level, voltage type and current level**. For example, when we talk about a **9VDC @ 500mA** power supply can provide **as much as 500mA of current** and the voltage will be at least **9V DC** up to that maximum current level. While it sounds simple, power supplies have a lot of little hang-ups that can be very tricky for the uninitiated. For example, unregulated supplies say they can provide 9V but really may be outputting 15V! The very common 7805 regulator datasheet claims it can regulate up to 1000 mA of current, but when you put a 15V supply on one side, it overheats and shuts down! This tutorial will try to help explain all about power supplies.

Why a power supply?

When you start out with electronics, you'll hear a lot about **power supplies** - they're in every electronics project and they are the backbone of everything! A good power supply will make your project hum along nicely. A bad power supply will make life frustrating: stuff will work sometimes but not others, inconsistent results, motors not working, sensor data always off. Understanding power supplies (boring though they may be) is **key** to making your project work!

A lot of people don't pay much attention to power supplies until problems show up. We think you should always think about your power supply from day one - How are you going to power it? How long will the batteries last? Will it overheat? Can it get damaged by accidentally plugging in the wrong thing?

Power supplies are all around you!

Unless you live in a shack in the woods, you probably have a dozen power supplies in your home or office.

Here is the power supply that is used in many apple products:

Here is a classic 'wall wart' that comes with many consumer electronics:

This is a massive power supply that's in a PC, usually you dont see this unless you open up the PC and look inside for the big metal box:

All these power supplies have one thing in common - they take high voltage 120V or 220V AC power and **regulate** or **convert** it down to say 12V or 5V DC. This is important because the electronics inside of a computer, or cell phone, or video game console dont run at 120V and they don't run on AC power!

So, to generalize, here is what the power supplies for electronics do:

1. They convert AC (alternating current) power to DC (direct current)
2. They regulate the high voltage (120-220V) down to around 5V (the common voltages range from 3.3V to 15V)
3. They may have fuses or other overcurrent/overheat protection

Hey, so if electronics can't run on AC, why doesn't wall power come in DC?

You may be wondering - "I have 20 wall adapters, this seems silly! Why not just have DC power come out of the wall at

5V?" Essentially, because modern electronics are very recent. for many many decades wall power was used to power light bulbs, big motors (like fridges, vacuum cleaners, washing machines, air conditioners), and heaters. All of these use AC power more efficiently than DC power. Also, different electronics need different voltages. So far its worked out better to have a custom power supply for each device although it is a little irritating sometimes!

AC/DC
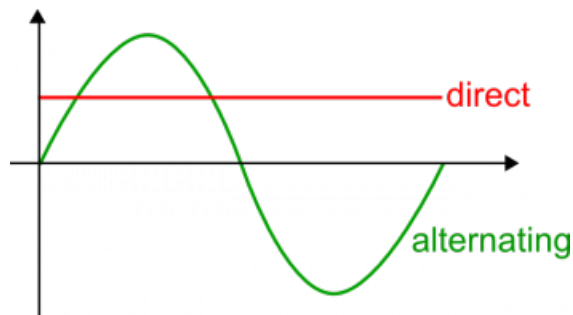
So the power coming out of your wall is high voltage AC but microcontrollers and servos and sensors all want low voltage DC. How shall we make it work? Converting between AC power and DC power requires different techniques depending on what the input and output is. We'll refer to this table:

Power type in	Power type out	Technique	Pros	Cons	Commonly seen...
High Voltage AC (eg. 120V-220VAC)	Low voltage AC (eg. 12VAC)	Transformer	Really cheap, electrically isolated	Really big & heavy!	Small motors, in cheaper power supplies before the regulator
Low Voltage AC (eg. 20VAC)	High voltage AC (eg ~120VAC)	Transformer	Same as above, but the transformer is flipped around	Really big & heavy!	Some kinds of inverters, EL wire or flash bulb drivers
High Voltage AC (eg. 120V-220VAC)	High voltage DC (eg. 170VDC)	Half or full wave rectifier	Very inexpensive (just a diode or two)	Not isolated	We've seen these in tube amps
Low Voltage AC (eg. 20VAC)	Low voltage DC (eg 5VDC)	Half or full wave rectifier	Very inexpensive (just a diode or two)	Not isolated	Practically all consumer electronics that have transformer-based supplies
High Voltage AC (eg. 120V-220VAC)	Low voltage DC (eg 5VDC)	Transformer & rectifier Combination of High→Low AC & Low AC→Low DC	Fairly inexpensive	Kinda heavy, output is not precise, efficiency is so-so	Every chunky wall-wart contains this

High Voltage AC (eg. 120V-220VAC)	Low voltage DC (eg 5VDC)	Switching supply	Light-weight, output is often precise	Expensive!	Every slimmer wall-wart contains this

Basically, to convert from AC to AC we tend to use a transformer. To convert from AC to DC we use a transformer + diodes (rectifier) or a switching supply. The former is inexpensive (but not very precise) and the later is expensive (but precise). Guess which one you're more likely to find in a cheaply-made device? :)

We left a few types out of this table because they're a little more esoteric or complex, such as the AC voltage doubler. These are still used but you're a little less likely to see them and they don't get used in power supplies you're likely to encounter.

Transformer-based AC/DC converters

The most common and inexpensive plugpack power supply type you'll see is the chunky transformer based plug. Whenever you buy some consumer electronics you'll be getting one of these:


These guys are **everywhere** - all sorts of voltage and current ratings. They're available for sale at any store just about, but there are some big things to watch out for! One is that the output voltage is not going to be 9V (for example) out of the box, that voltage rating is just the minimum output for the current rating (200mA for example). And also, the output is going to have a lot of ripple on it!

Before we talk precisely about these guys, lets go back in time to when engineers had to build their power supplies with their bare hands!

The good old days!

Back a couple decades ago, the only way to build a power supply was to start a big chunky 120VAC/12VAC transformer. The transformer was used to bring the high voltage from the wall down to a less dangerous level. Then diodes and capacitors were used to turn the AC into DC.

Transformers
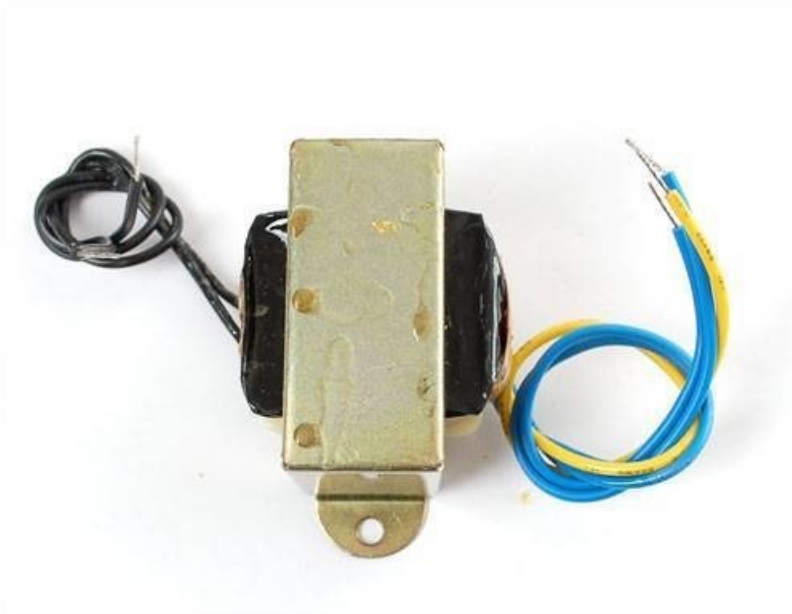
We aren't going to get into the heavy detail of the electromagnetic theory behind transformers except to say that they are made of two coils of wire around a chunk of iron. If the number of coils are the same on both sides then the AC voltage is the same on both sides. If one side has twice the coils, it has twice the voltage. They can be used 'backwards' or 'forwards'! For more detailed information, be sure to check out the wikipedia page (https://adafru.it/alf).

To use it, one half would get wired up to the wall (the 'primary' 'high side')

and the other half would output 12V AC (the 'secondary' 'low side'). The transformer functioned in two ways: one it took the dangerous high voltage and **transformed** it to a much safer low voltage, second it **isolated** the two sides. That made it even safer because there was no way for the hot line to show up in your electronics and possibly electrocute you.

We'll use a schematic symbol to indicate a transformer, its two coils inside which are drawn out, the schematic symbol will have the same number of coils on either side so use common sense and any schematic indicators to help you out in figuring which is primary and which is secondary!


Half wave rectification

Now that the voltage is at a non-electrocutey level of around 12VAC it can be converted into DC. The easiest and cheapest way to convert (also called **rectify**) AC to DC is to use a single diode. A diode is a simple electronic 'valve' - it only lets current flow one way. Since AC voltage cycles from positive to negative and we only want positive, we can connect it up so that the circuit only receives the **positive half** of the AC cycle.

You'll want to use a power diode such as a 1N4001 (https://adafru.it/cuU) , they're extremely common and can put up with a lot of abuse. The side with the silver stripe matches the schematic symbol side that the 'arrow' in the diode symbol is pointing to. That's the only direction that current can flow. The output is then chopped in half so that the voltage only goes positive.
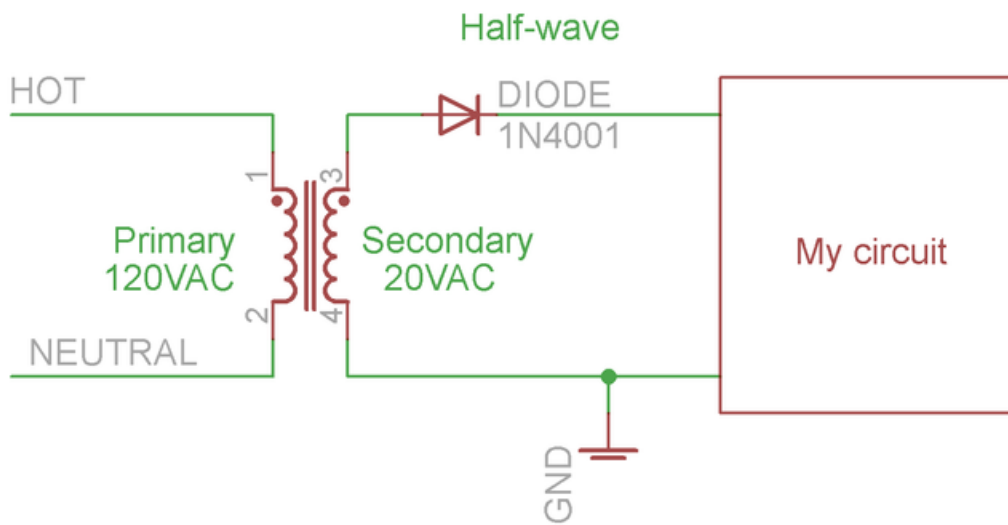

This will convert

into

half-wave rectified
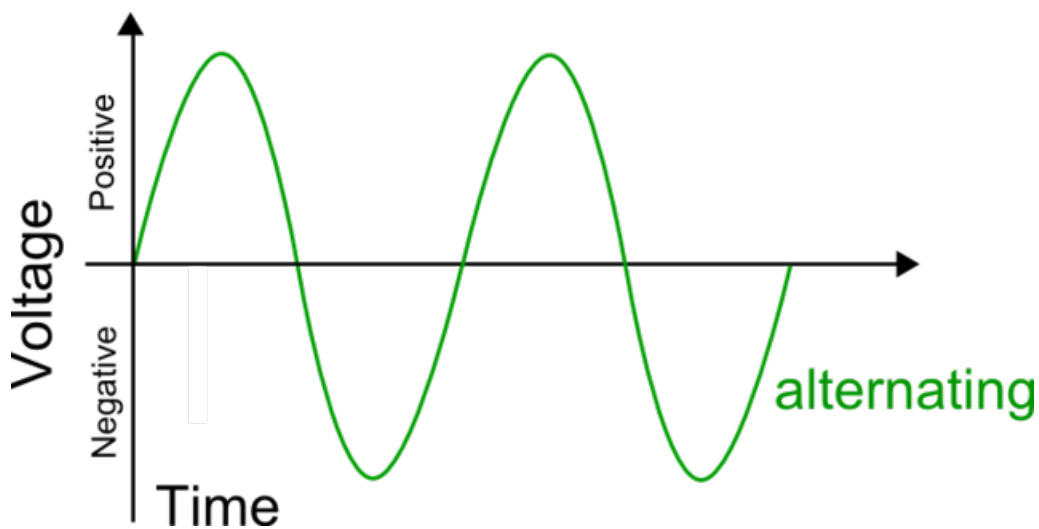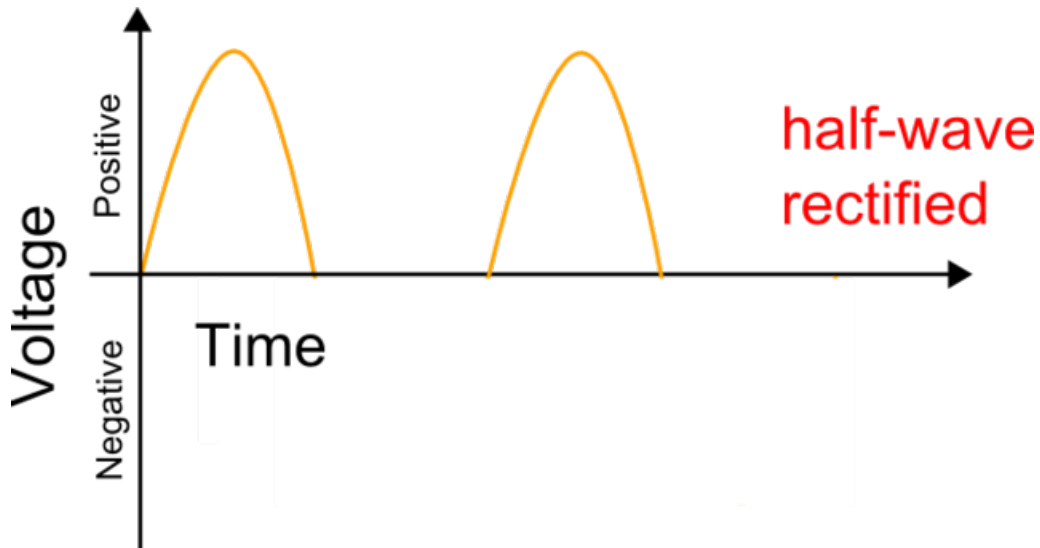
What we have now isnt really AC and isn't really DC, its this lumpy wave. The good news is that it's only positive voltage'd now, which means its safe to put a capacitor on it.

This is a 2200 microFarad (0.0022 Farad) capacitor, one leg has (-) signs next to it, this is the negative side. The other side is positive, and there should never be a voltage across is so that the negative pin is 'higher' than the positive pin or it'll go POOF!
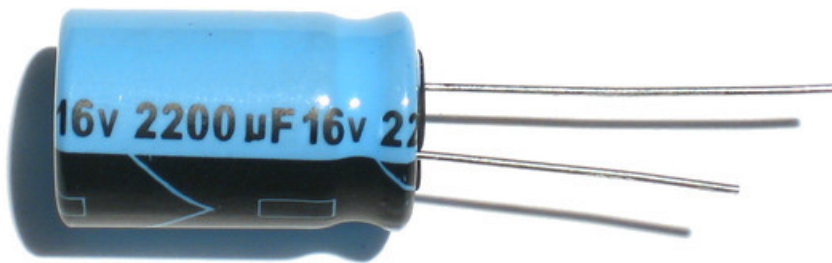
A capacitor **smooths** the voltage out, taking out the lumps, sort of how spring shocks in car or mountain bike reduce the bumpiness of the road. Capacitors are great at this, but the big capacitors that are good at this (electrolytic) can't stand negative voltages - they'll explode!

Full-wave
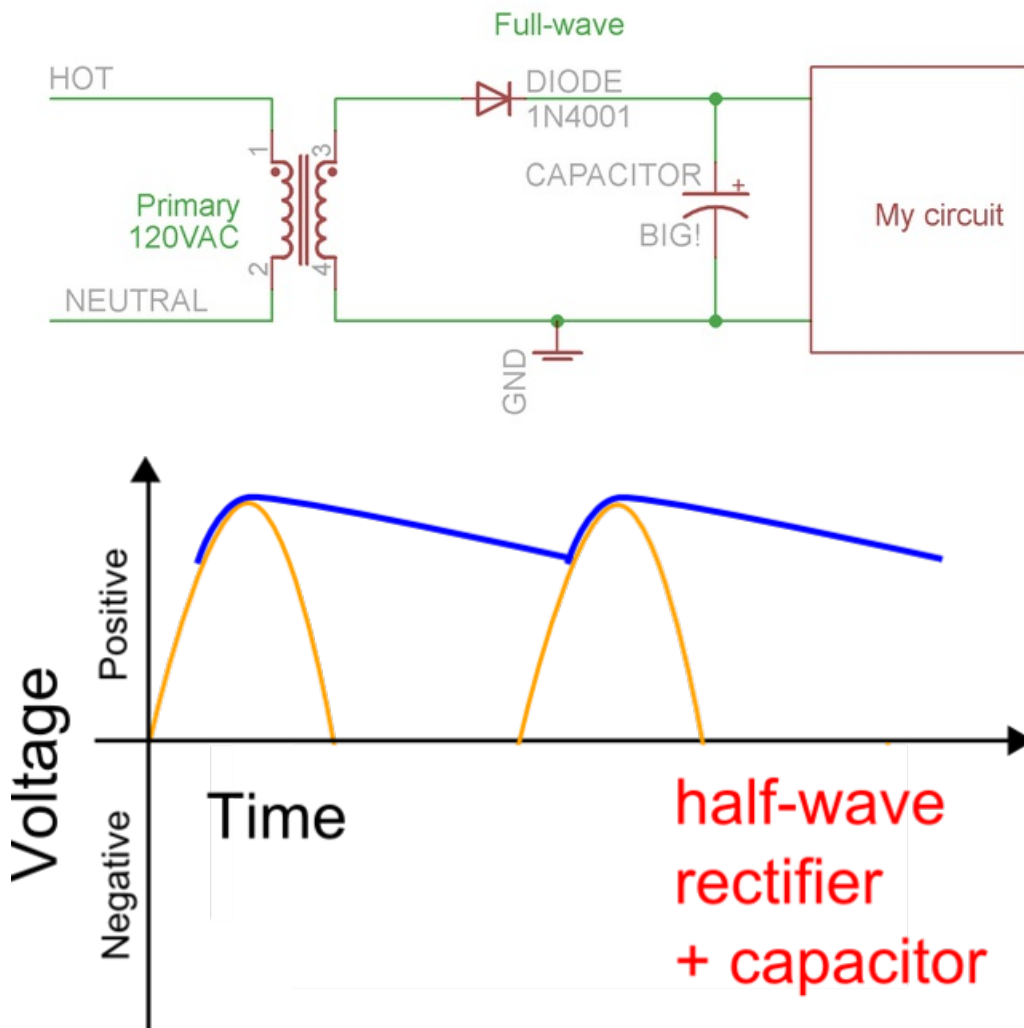
Because the voltage is very uneven (big ripples), we need a really big electrolytic-type capacitor. How big? Well, there's a lot of math behind it which you can read about (https://adafru.it/alh) but the rough formula you'll want to keep in mind is:

Ripple voltage = Current draw / ((Ripple frequency) * (Capacitor size))

or written another way

Capacitor size = Current draw / ((Ripple frequency) * (Ripple Voltage))

For a half wave rectifier (single diode) the frequency is 60 Hz (or 50 Hz in europe). The current draw is how much current your project is going to need, maximum. The ripple voltage is how much rippling there will be in the output which you are willing to live with and the capacitor size is in Farads.

So lets say we have a current draw of 50 mA and a maximum ripple voltage of 10mV we are willing to live with. For a half wave rectifier, the capacitor should be **at least** = 0.05 / (60 * 0.01) = 0.085 Farads = **85,000 uF**! This is a **massive** and expensive capacitor. For that reason, its rare to see ripple voltages as low as 10mV. Its more common to see maybe 100mV of ripple and then some other technique to reduce the ripple, such as a linear regulator chip.

You don't have to memorize that formula, but you should keep the following in mind: When the current goes **up** and the capacitor stays the same, the ripple goes **up**. If the current goes **up** and you want the ripple the same, the capacitor must also **increase**.
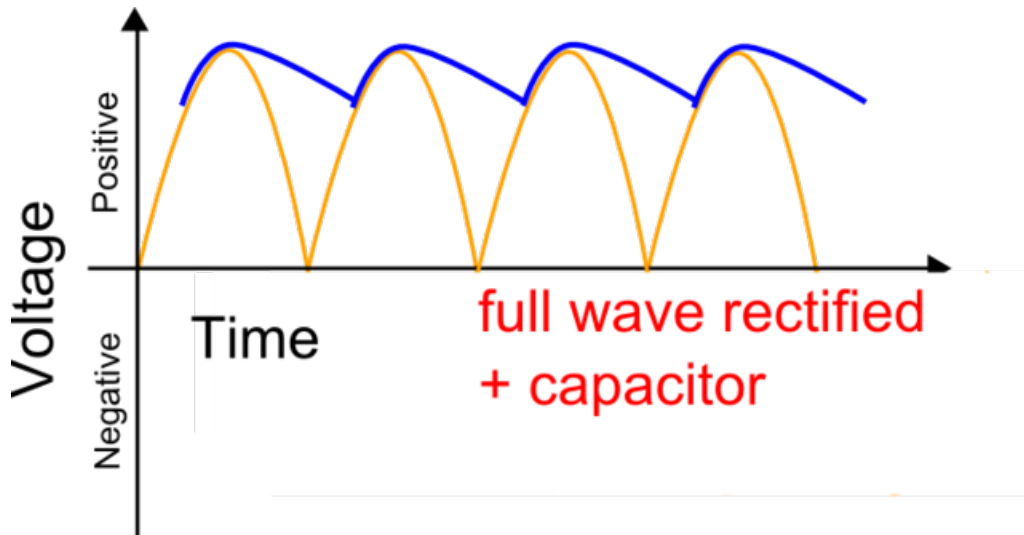
Full wave rectifiers

One thing that can be done to reduce the ripple/capacitor size by half is to use a full wave rectifier instead of a half wave. A full wave rectifier uses 4 diodes arranged in a peculiar way so that it both lets the positive voltage through **and** manages to 'flip over' the negative voltages into positive.
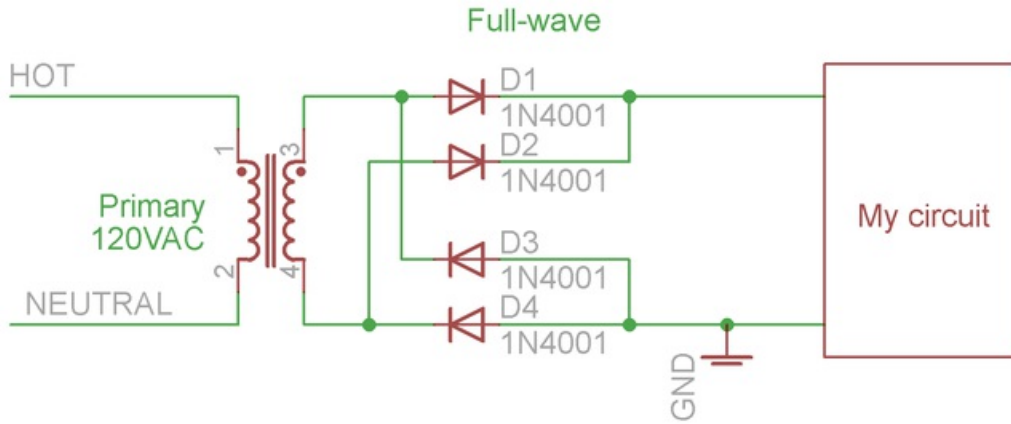
So now we get:
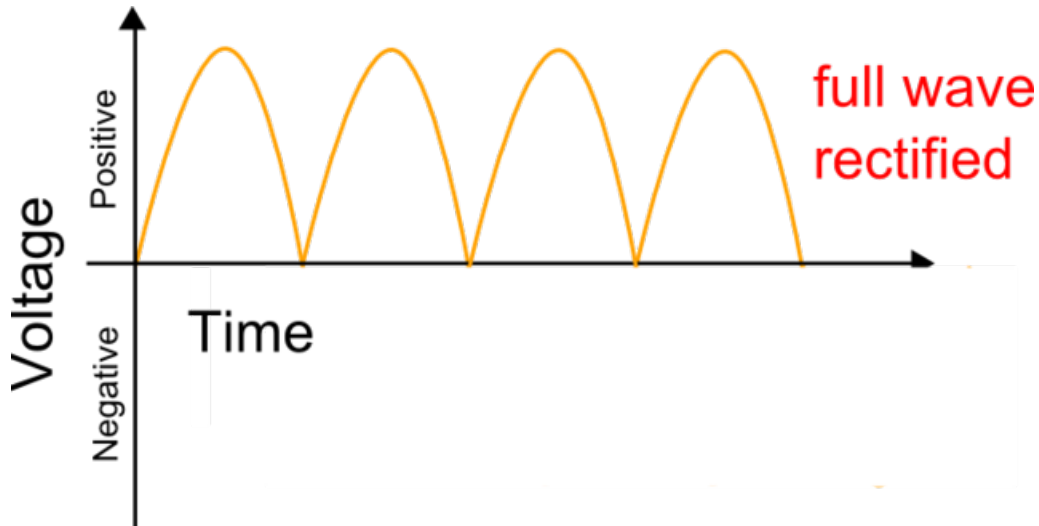
As you can see, there are twice as many humps - there isnt that "half the time, no voltage" thing going on. This means we can divide the calculated capacitor size to half of what it was in the previous.

full wave rectified + capacitor

Basically, a full wave rectifier is way better than a half wave! So why even talk about half-wave type rectifiers? Well, because they're useful for a few other purposes. In general, you're unlikely to see an AC/DC converter that uses a half wave as the cost of the diodes makes up for the saving in capacitor size and cost!
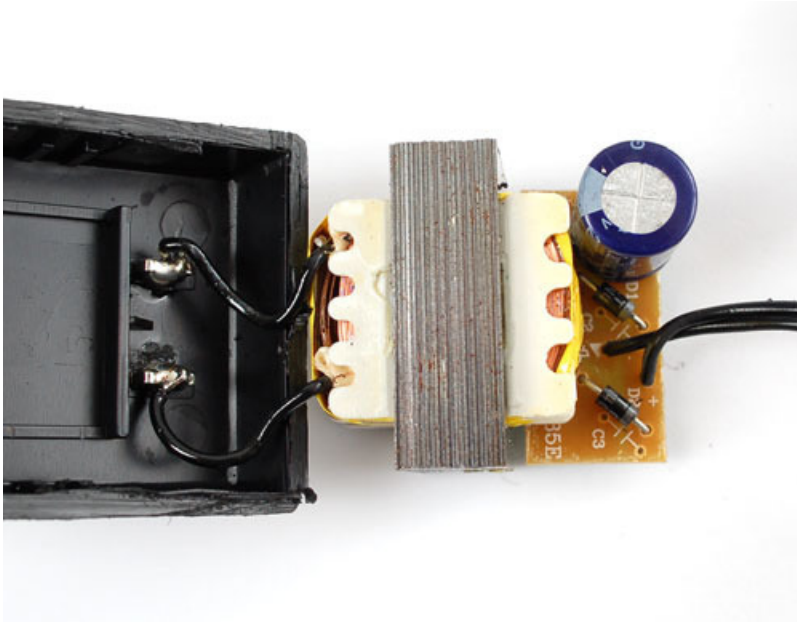
The transformer AC/DC in practice

OK now that we've reviewed transformers, diodes when used as rectifiers and big capacitors, lets look at a chunky plugpack again. This time, we'll look inside by cutting it in half! This power supply is rated at **9VDC @ 200mA.**

We can pull it out completely to see the circuit board parts.

Wow so this looks really familiar, right? From left to right, you can see the wires that come into the transformer from the wall plug, the transformer output has two power diodes on it and a big capacitor (2,200uF). You might be a little puzzled at the **two** diodes - shouldn't there be **four** for a full-wave rectifier? It turns out that if you have a special transformer made with a 'center tap' (a wire that goes to the center) you can get away with using only two diodes (https://adafru.it/ali) . So it really is a full wave rectifier, just one with a center-tap transformer.

These transformer-based plug-packs are **really cheap** to make - like on the order of under $1!

Testing the 9V supply

So now we will take a fresh power supply (don't use one you sawed in half, of course) and measure the output voltage with a multimeter.

Yow! 14V? That's not anything like the 9V on the package, is this a broken wall wart? No! Its totally normal! Transformer-based wall adapters are not designed to have precision outputs. For one thing, the transformer, if you remember, is made of coils of wire. The coils for the most part act like inductors but they still have some small resistance. For example, if the coil is 10 ohms of resistance, then 200 mA of current will cause V = I * R = (0.2 Amps) * (10 ohms) = 2 Volts to be lost just in the copper winding! Another thing that causes losses is the metal core of the transformer becomes less efficient as the amount of current being transformed increases. Altogether, there are many inefficiencies that will make the output fluctuate. In general, the output can be as high as **twice** the 'rated' voltage when there is less than 10mA of current being drawn.
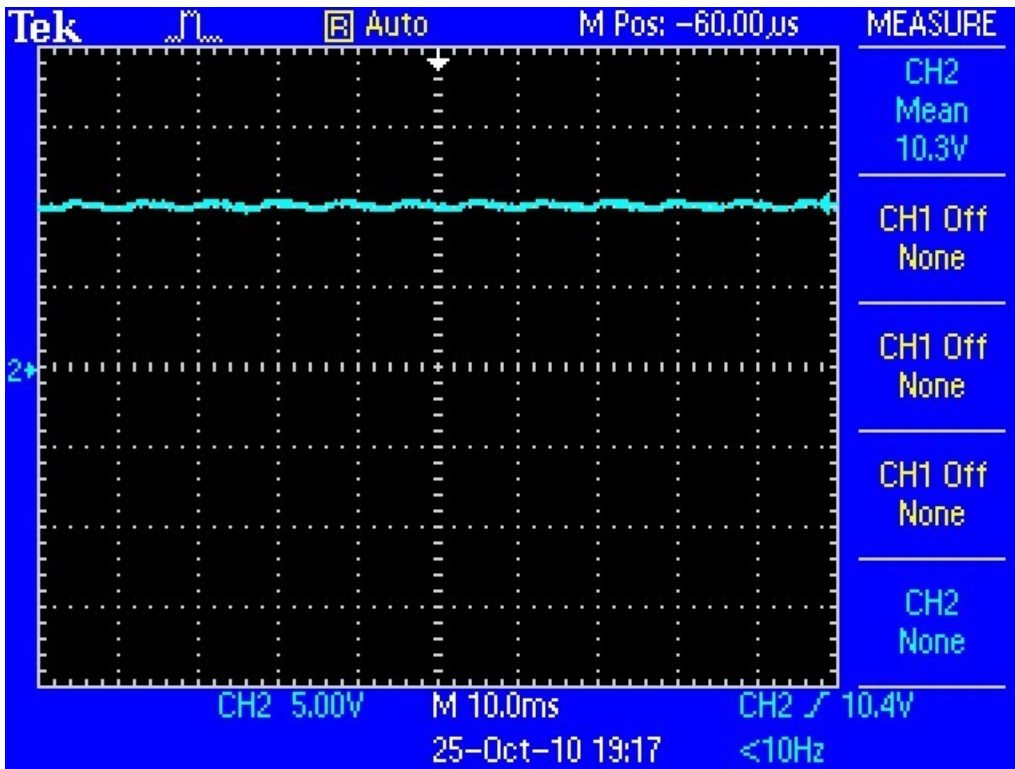
Let's look in detail

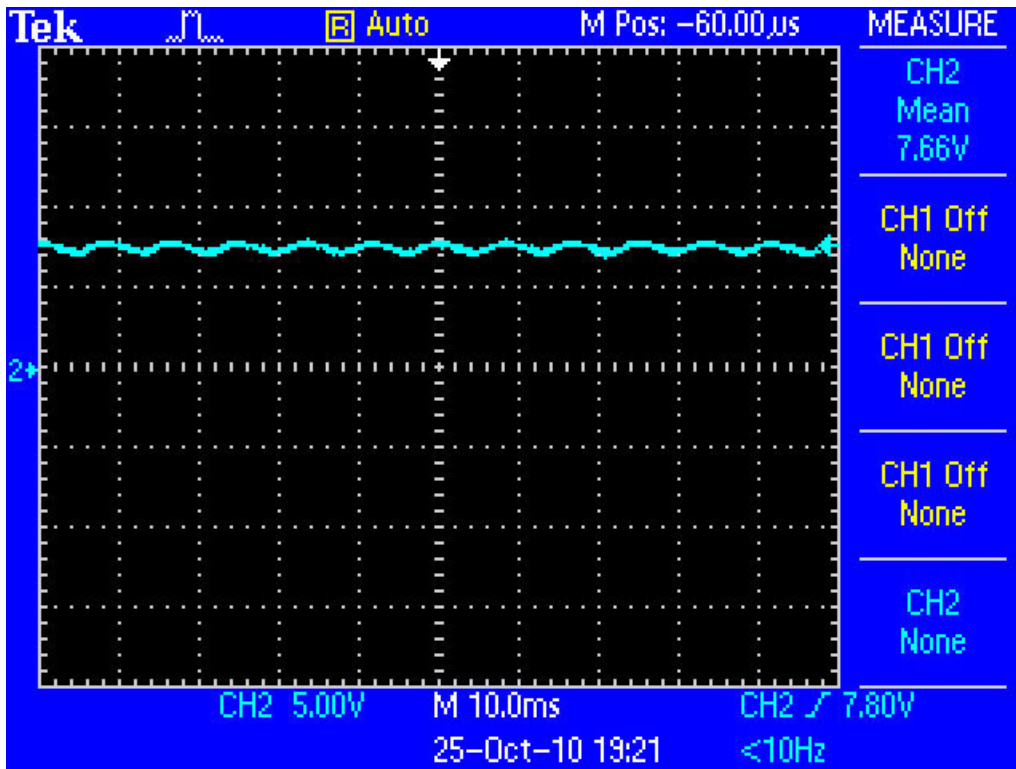Lets look on an oscilloscope, that way we can see in detail what is going on.
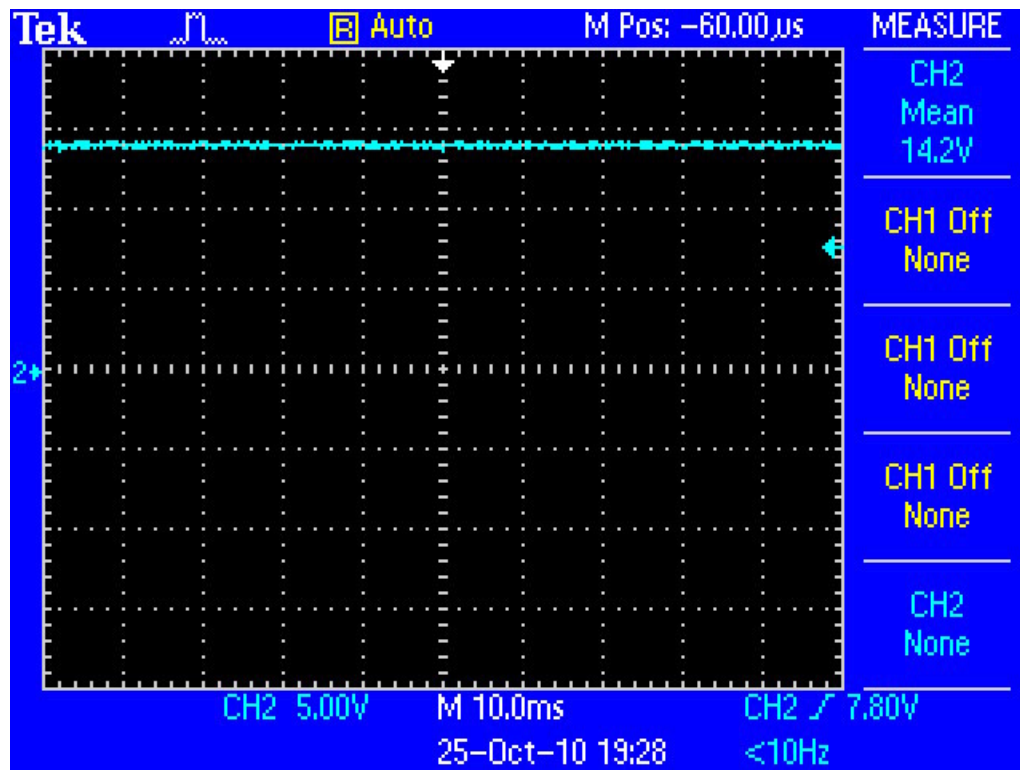
With no current being drawn on the supply, the voltage output is about 14V
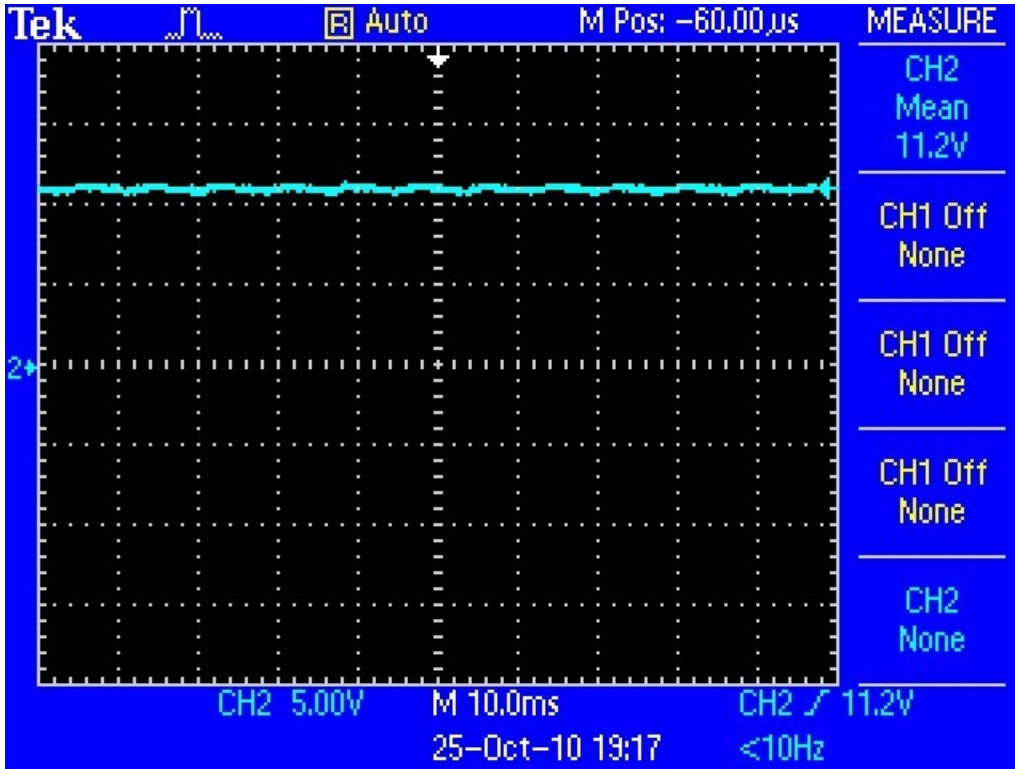
When I connected a 100 ohm resistor (110 mA draw) from the positive pin to the negative pin, it dropped to 11.2V

Connecting a 60 ohm resistor (~160 mA draw), it goes down to 10.3V

With 35 ohms (230 mA draw) the voltage plummets to 7.7V!

As the resistance gets smaller and smaller, the current draw gets higher and higher and the voltage **droops** (that's the technical term for it!) You can also see the ripple increase as the current goes up.

Now we can at least understand the thinking behind saying "9V 200mA" on the label. As long as we are drawing **less than 200mA** the voltage will be **higher than 9V.**

What does this mean for you?

OK so after all that work, you're wondering why does this even matter? The reason it matters is that everywhere you look are these wall warts that are 'unregulated' and thus extremely suspicious. You simply can't trust 'em to give you the voltage you want!

For example, let's say you have a microcontroller project and it requires 5V power as many DIY projects do. You shouldn't go out and buy a 5V transformer supply like the one above and just stick the power output into your microcontroller - you'll destroy it! Instead, you will need to build a 5V regulator like the common LM7805 that will take the somewhere-around-9V from the transformer and convert it to a nice steady 5V with almost no ripple.

So here is what you should always do:

1. Always check your power supply brick with a multimeter to see what the maximum voltage is
2. Assume that the voltage can be twice as high as you expect
3. Assume that the voltage will droop as you draw more and more current
4. If you're using a brick for low-power usage, say your circuit draws 100mA max, find one that has a very similar current rating.

You might be wondering well why on earth doesn't someone make a power plug that takes a transformer and some diodes and a LM7805 and that will give you a nice 5V output instead of having everyone build it into the project

circuit? While it's an interesting idea there are a few reasons they don't do that. One is that the enclosed wall adapter would overheat. Another is that some projects need more than one voltage, say 5V and 3.3V both. But in the end, its probably for manufacturing simplicity. The factory that makes the wall plugs makes 100's of thousands in predictable sizes and rates, each country has plenty of factories to make the right plug packs for the wall voltage and plug style. The designers of, say, the DVD player have an easier time of it when they can just say "anything above 7V and below 20V input will work for us" and the plug-pack maker matches them up with the closest thing they already make.

Nowadays, there are switch-mode power plugs that solve much of this problem. They are thinner and lighter than transformers and have almost no heating problems so they can have precise outputs that don't fluctuate. However, circuit-wise they are much more complex which means they're also much more expensive than transformer-supplies, perhaps 5-10x the price, and have a downside that they're 'noisier' electrically. But, because the parts and assembly cost is going down, they're much more popular than they were even 10 years ago.