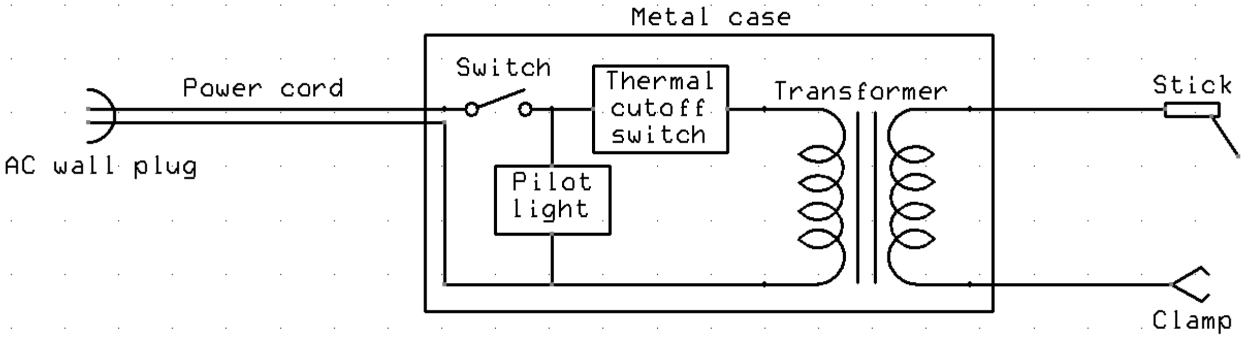
Converting a Lincoln “Hobby-Weld” AC stick welder to regulated DC

I inherited a Lincoln “Hobby-Weld” AC stick welder. It plugs into a normal 120V AC outlet. It has only one control, an on-off switch. There is no way to adjust the flow of current through the stick. The picture on the left shows the unit with the cover removed before I began working on it. The picture on the right is a detail of the front panel.

The following picture is a view into the left side of the unit. The whole welder is not much more than a big transformer. The two wires coming out at the bottom are the two ends of the secondary winding. They exit through the front panel, with the ground clamp on one wire and the stick handle on the other.

The following schematic diagram shows the original circuit. There are only three components inside the metal case. The switch is an on-off rocker switch with a built-in red light which glows when the unit is switched on. 120V AC from the wall socket is wired directly to the primary winding of the heavy-duty transformer. In one of the primary leads, there is a small temperature-controlled switch which opens if the inside of the case gets too hot.



The following picture is a view into the right side of the unit. The AC power cord enters the unit through the rear panel, on the right-hand side of the photograph. The on-off switch and pilot light are mounted high on the front panel, on the left-hand side of the photograph. The thermal switch is the cylindrical component mounted low down on the primary coil.

A table on the front panel sets out the following specifications for the unit.

Input power: current of $20A$ at a voltage of $115V$ and a frequency of $60Hz$
Output power: current of $50A$ at a voltage of $25V$

The output power is the maximum this unit can deliver. Power is the product of current and voltage $P = I \times V$, so the transformer can deliver up to:

$$P_{out} = 50A \times 25V = 1{,}250\ Watts$$

The input power is the maximum the unit should draw. The unit should draw a maximum of:

$$P_{in} = 20A \times 115V = 2{,}300\ Watts$$

The difference between the input and output power is $1{,}050\ Watts$. This is potentially the amount of heat the transformer could dissipate, which arises from inefficiency in its operation. There is resistance in the wires, eddy currents in the iron core, and so forth, all of which convert electrical energy into heat inside the transformer.

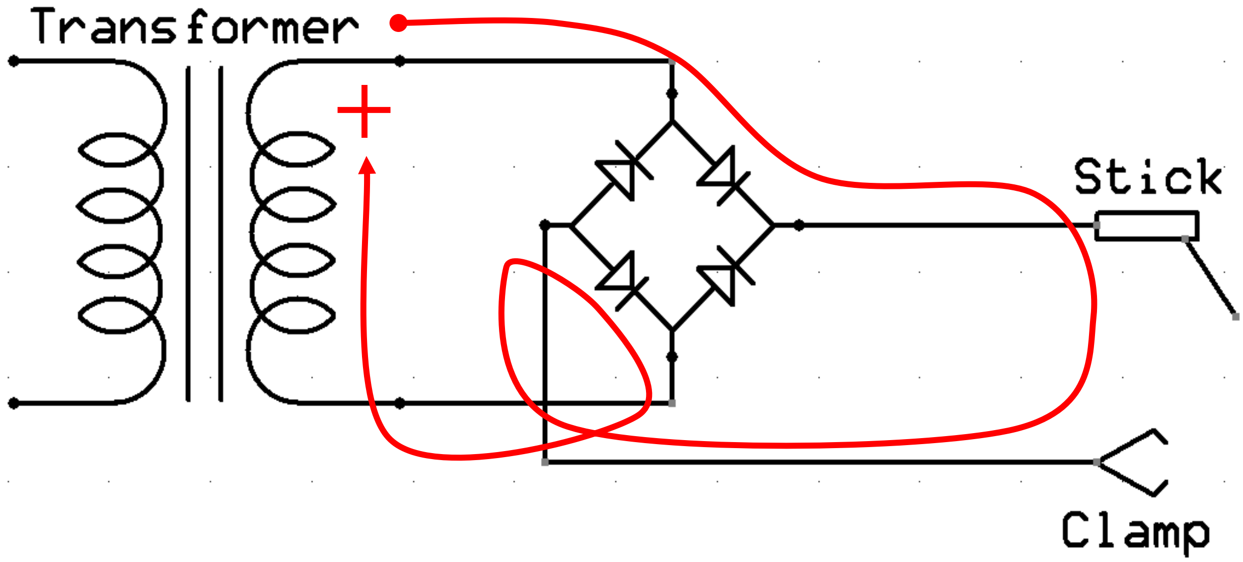
Goals for converting the welder

I wanted to make two types of modifications to the welder:

1. To change the output from AC (alternating current) to DC (direct current). In fact, I will go further than usual, and regulate the output DC.
2. To provide a means for controlling the amount of current flowing through the circuit.

Rectified direct current

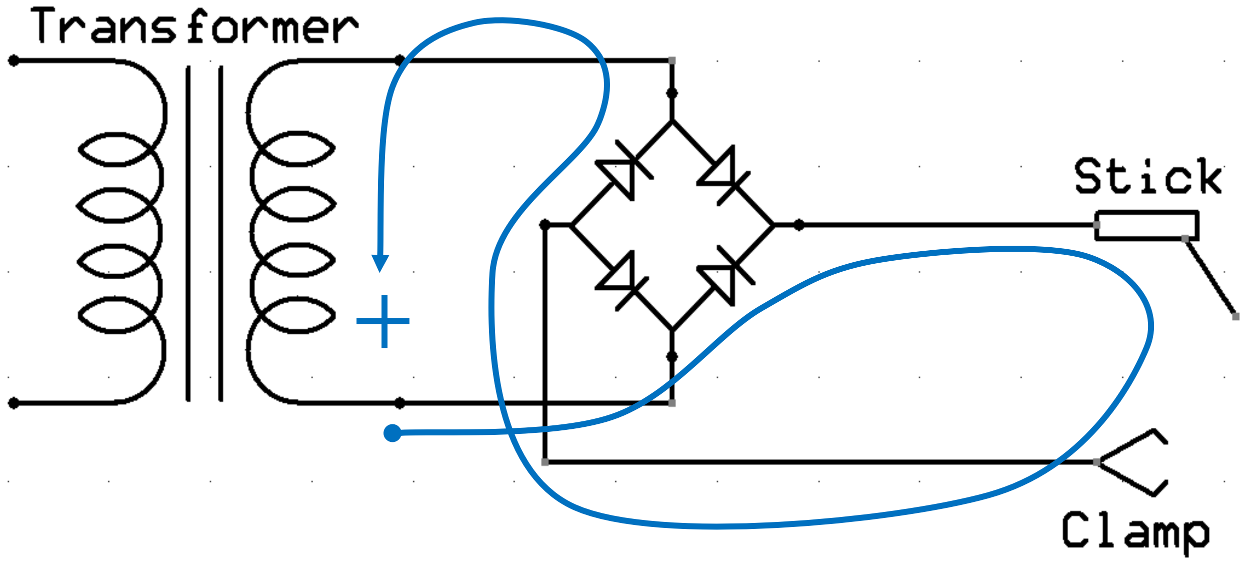
Most DC welders produce a very crude form of direct current. All they do is rectify the alternating current coming out of the secondary coil. A single component is enough to do that. The following schematic shows how a “bridge rectifier” is wired to the secondary winding of the transformer.



A bridge rectifier is simply a set of four diodes arranged in a particular pattern. Remember that a diode is a two-terminal component which permits current to flow in one direction but not the other.

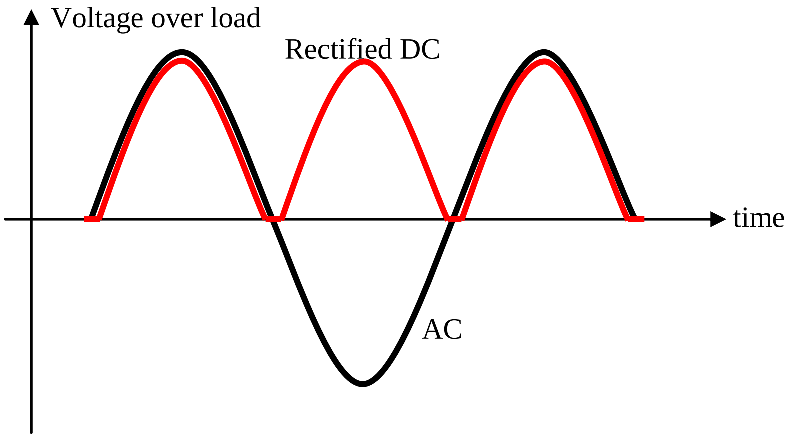
For half of each cycle of the alternating current, the top end of the transformer will be at a higher voltage than the bottom end. The red arrow shows the path of the current during this half-cycle. It flows from the top end of the transformer, down through the upper-right diode and through the stick into the workpiece. It then flows back into this circuit, downwards through the bottom-left diode, from whence it returns to the transformer, entering at the bottom end.

During the other half of each alternating current cycle, the bottom end of the transformer will be at a higher voltage potential than the top end. The following schematic shows the flow of current (in blue) during these half-cycles. This time, the current flows through the bottom-right diode and the top-left diode.



It is important to note that the current flows in the same direction through the workpiece – from the stick to the clamp – in both cases. This is why it is called direct current, rather than alternating.

During each half-cycle, two diodes conduct. However, it is a different pair of diodes during each half-cycle. An ideal diode would allow current to pass through without any voltage drop. Real diodes suffer from a voltage drop. For heavy-duty diodes like the ones required in this kind of application, the voltage drop will be about one volt per diode. Since the current always flows through two diodes in series, the peak voltage applied to the workpiece will be about two volts less than the peak unrectified AC voltage. The following graph illustrates the waveforms of the voltage applied to the workpiece by the AC circuit (in black) and by the rectified DC circuit (in red).



At every moment in time, the rectified voltage will be about two volts less than the alternating voltage. There will be a short period of time at the beginning and end of each half-cycle when the alternating current has an amplitude less than two volts, during which times no current at all will flow in the rectified DC circuit. Each diode needs to be forward-biased by about a volt before it will allow current to pass through.

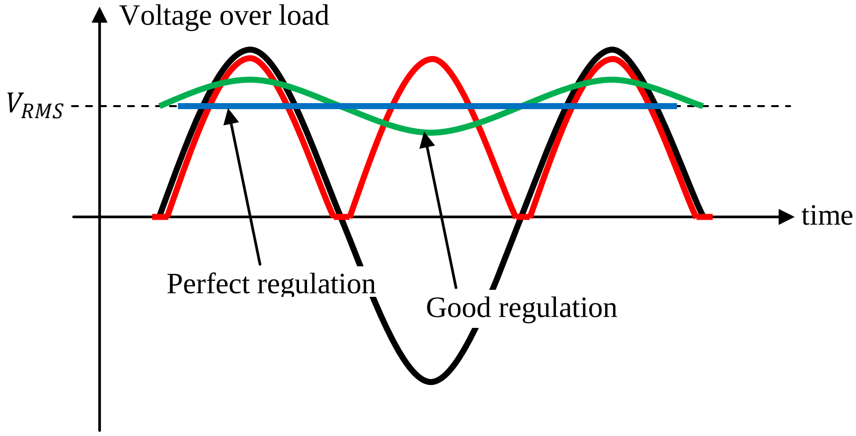
Why is a rectified DC welder better than an AC welder?

DC welders produce better welds and better looking welds than simple AC welders[1]. Consider the arc of plasma between the tip of the stick and the workpiece. When using an AC welder, the current flows first in one direction, then in the other direction, then in the first direction again, as so on. Each start-stop cycle interrupts the production of heat which melts the stick and the pool. Since rectified DC current has less variation than AC current, the heating will be more uniform and the resulting welds more structurally sound. Rectified DC current also reduces the strength of the electric and magnetic jolts which accompany the sudden starting and stopping of current and which lead to splatter.

If rectification is good, is regulation even better?

The answer is: yes. "Rectification" means that the current flows in only one direction. It does not mean the current is constant, like that delivered by a battery. A perfectly constant current through the plasma would indeed produce the best possible weld.

"Regulation" is the process of reducing the variability in a direct current. The following graph shows the same AC and rectified DC voltages as the previous graph, but also two more waveforms which show different degrees of regulation.



With perfect regulation, the voltage (in blue) is absolutely constant. With good regulation (in green), the variations in the voltage are reduced to, say, 10% or 25% of the peak amplitude.

Let me mention the particular voltage I have labelled V_{RMS}. In a sense, it is the average voltage, where "average" is defined in a special way. If we set aside the three-volt drop over the diodes (the electrical power expended inside the diodes is converted into heat), all four voltage waveforms will generate the same amount of electrical power in a resistive load (i.e., the workpiece). Remember Ohm's Law and the Power Law:

Ohm's Law: $Voltage = Current \times Resistance$
Power Law: $Power = Voltage \times Current$

These relationships hold when the voltage is constant. So long as the resistance is a fixed value, the current will also be a fixed value. Since the voltage and current are both fixed values, the power being consumed will also be a fixed value. This is the case with the perfectly-regulated waveform.

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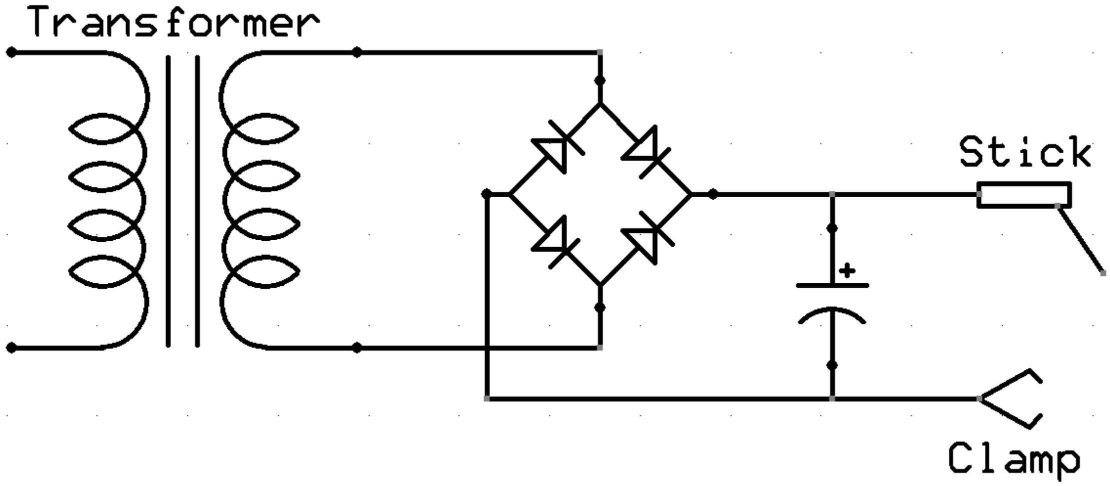
[1] But there are some high frequency AC welders in which the frequency plays an important part in their operating principle.

However, Ohm's Law and the Power Law also hold at every instant in time, even when the voltage and current change with time. So long as the resistance is a fixed value, the current will change in exact proportion to the voltage. What one does is multiply the instantaneous voltage by the instantaneous current to calculate the instantaneous power being generated, and then add up the instantaneous power over the duration of one complete cycle of the AC waveform. (Every cycle is the same, so what happens during one cycle is typical of what happens during all cycles.) It turns out that the average power generated during the cycle corresponds exactly to the power generated by a constant voltage of V_{RMS}. The subscript is an acronym for "root-mean-square" and summarizes the mathematical steps needed to do an average of the power over one complete cycle.

The V_{RMS} voltage is not one-half of the peak voltage of the AC waveform. It is higher than that, more like 71% of the peak voltage.

I will implement the simplest possible method of regulation. It involves the use of a capacitor, as shown in the following schematic. The capacitor is wired across the output from the rectifier. At those times when the instantaneous voltage supplied by the secondary winding is greater than the RMS value, some of the power will be used to charge up the capacitor, reducing the voltage drop across the workpiece. At other times, when the instantaneous voltage supplied by the transformer is less than the RMS value, the capacitor will start to discharge, adding to the current flowing through the workpiece. The capacitor serves as a storage device for energy, keeping the power being dissipated in the workpiece more uniform than otherwise. Despite its simplicity, this arrangement gives surprisingly good regulation.

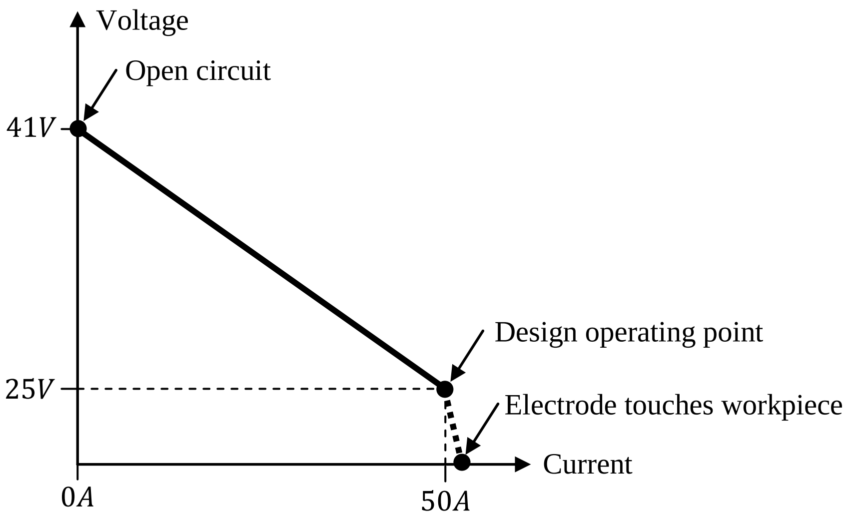


To choose a capacitor, we need to know the internal resistance of the transformer

The currents flowing through a welder are very large. Even small resistances have a significant effect on performance. In many applications, the internal resistance of a transformer can be ignored, but not here. Fortunately, there is a way to estimate the internal resistance of the Hobby-Weld's transformer.

Using a voltmeter and some care, I measured the voltage drop between the stick and the clamp while the unit was turned on but not connected to the workpiece. I measured a voltage of $41V$. This is called the "open circuit voltage" because it is measured while no current is flowing through the secondary winding of the transformer. In other words, while the secondary circuit is open.

The table on the front panel of the unit gave us one combination of voltage and current at which the welder can operate. That is the design operating point: $50A$ at $25V$. The open-circuit reading gives us another. I have plotted these two points on the following V-I characteristic curve for the transformer. Voltage is measured along the vertical axis. Current is measured along the horizontal axis.



The welder is said "to operate" at points along the heavy black line. It will be a straight line if the "lossy" components of the circuit can be modelled as resistances.

I have shown a short dotted stub downwards from the $(50A, 25V)$ design operating point. One goes down this line, to zero volts, if the electrode touches and then sticks to the workpiece. The transformer is not designed to operate here. Even though the voltage is zero, the transformer cannot and will not produce an infinite current. In fact, the current will not get much above the design current of $50A$. Since there is no significant voltage drop over the workpiece, the power will not be dissipated inside the workpiece, but inside the windings of the transformer, where it will be converted into heat. If the stick remains stuck to the workpiece for very long, the thermal protection switch will open and the primary current cut off (if one is lucky) or the transformer will burn itself out (if one is not).

We can calculate two important resistances from the graph.

1. The internal resistance of the transformer

   When no current flows through the transformer, there is no voltage drop over the transformer's internal resistance. The $41V$ voltage drop I measured arises from the inductance of the windings, not from the normal, or "Ohmic", resistance[2]. On the other hand, when $50A$ of current flows through the secondary winding of the transformer, the voltage drop over the internal resistance is $16V$. The difference, being $41V - 16V = 25V$, is the voltage drop between the stick and the clamp. The internal resistance can be calculated using Ohm`s Law:

$$R_{int} = \frac{change\ in\ voltage}{change\ in\ current} = \frac{16V}{50A} = 0.32\ Ohms$$

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[2] Inductance is the tendency of a coil to resist changes in current. Like a normal resistor, it resists current. Unlike a normal resistor, this type of resistance is not permanent. Energy removed from the current flow by the inductance is stored in a magnetic field. That energy will be returned to the current flow when the magnetic field shrinks. This form of resistance, which only exists if the current changes, is called "reactance".

2. The designer`s estimate of the resistance in the stick and workpiece

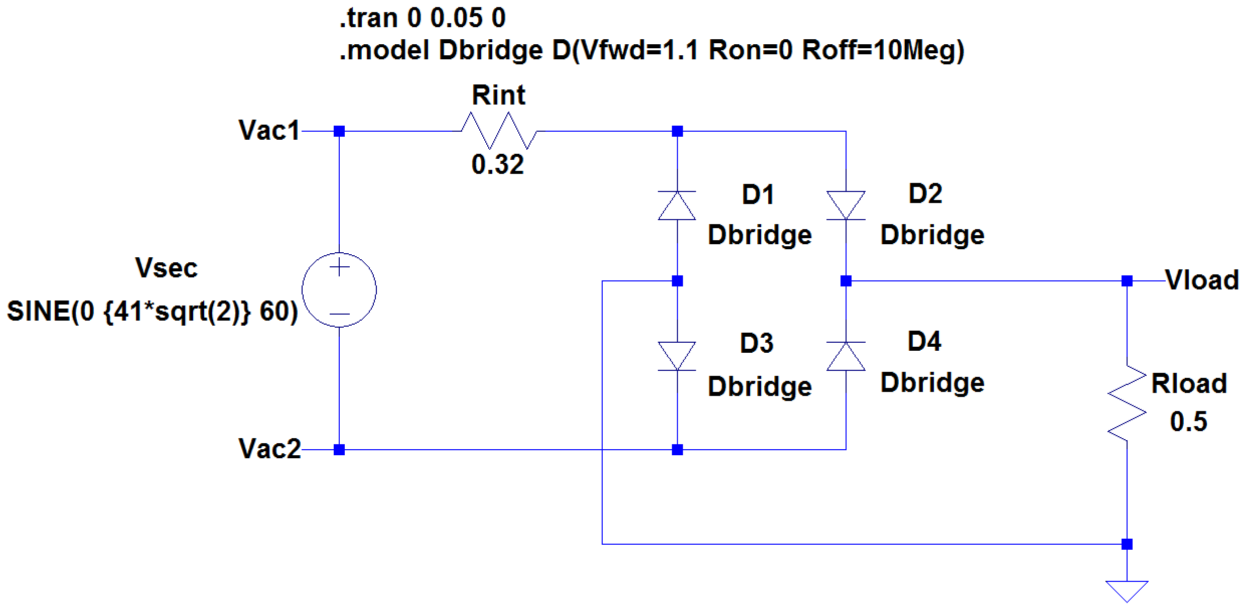
The designers of the Hobby-Weld assumed that, in the worst case, the electrical load, which is comprised of the stick, the workpiece, the clamp and the connecting cable, will draw $50A$ of current when $25V$ is available. The series resistance of the stick, workpiece, clamp and cable can be calculated using Ohm`s Law once more:

$$R_{load} = \frac{applied\ voltage}{current\ drawn} = \frac{25V}{50A} = 0.5\ Ohms$$

The designers assumed this would be the worst case. Here, "worst case" means the case when the current drawn is at its maximum, and the demands imposed on the transformer are most extreme. When the load resistance (that is, the series combination of the stick, workpiece, clamp and cables) is greater than 0.5Ω, the current drawn will be less than $50A$ and the transformer will not have to work as hard.

An LTSpice model for the secondary circuit – Rectification only

To understand in a little more detail how things will work, I constructed an LTSpice model. I constructed the model in two stages. In this section, I dealt with rectification only. In the next section, I will describe regulation. The following LTSpice schematic shows the first stage. Let me explain the various components which appear in the schematic.



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.tran 0 0.05 0
.model Dbridge D(Vfwd=1.1 Ron=0 Roff=10Meg)
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On the left-hand side is a source of voltage named Vsec. It represents the voltage which is generated by the inductance of the secondary winding. Since we know what comes out of the secondary winding, we do not need to model the primary winding, the on-off switch or the thermal protector. The inductance of the secondary winding generates a sine waveform with a $41V$ RMS voltage at a frequency of $60\ Hz$. The peak voltage of the sine waveform is a factor of $\sqrt{2} = 1.4$ greater than the RMS voltage. 1.4 is the reciprocal of the factor 71% I mentioned above.

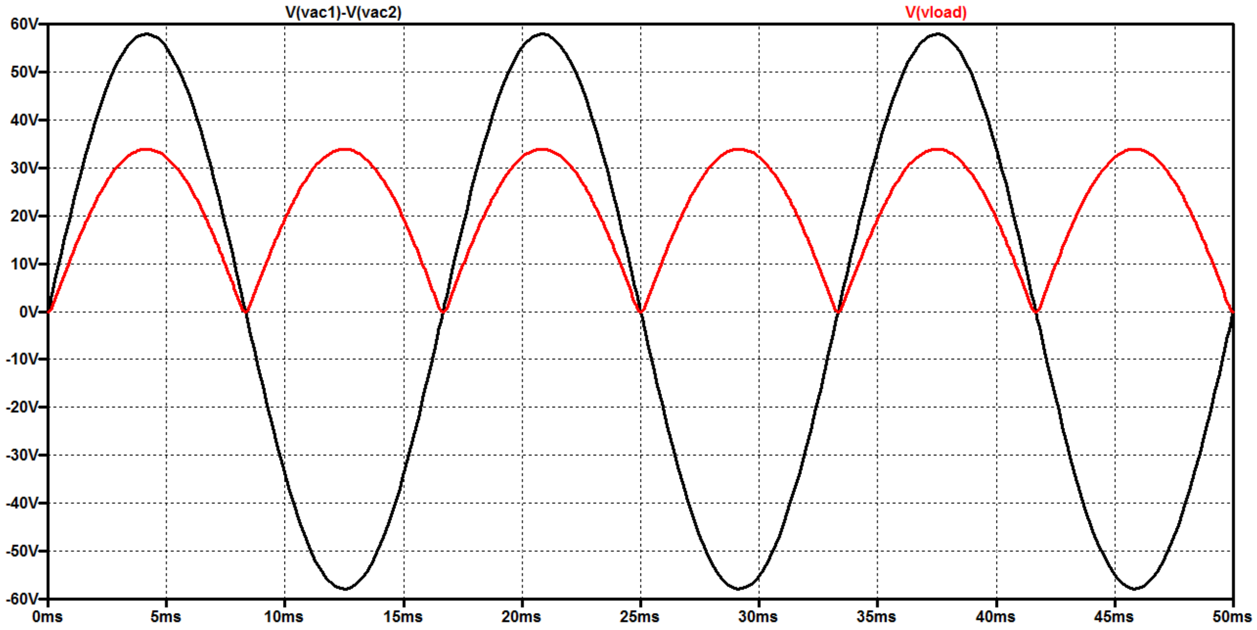
The internal Ohmic resistance of the secondary winding is represented by the 0.32Ω discrete resistor named Rint.

The bridge rectifier is represented by four diodes, wired in the appropriate pattern. The bridge rectifier I used during construction is Digikey's part #GBPC1050-BPMS-ND. From its datasheet, I see that the forward voltage drop is $1.1V$ per "leg", meaning per diode. This bridge rectifier has a reverse blocking voltage of $700V_{RMS}$, which is vastly higher than this circuit requires. But, it is rated up to $50A$ of current, which is the important parameter for us.

I have combined the resistances of the stick, workpiece, clamp and cables into the 0.5Ω resistor Rload.

The .tran directive tells LTSpice to simulate the circuit for $50ms$, or 50 milliseconds. The length of each cycle in the $60\ Hz$ driving voltage is $1/60 = 16.7ms$. Therefore, the simulation will cover about $50ms/16.7ms \cong 3$ complete cycles of the driving voltage.

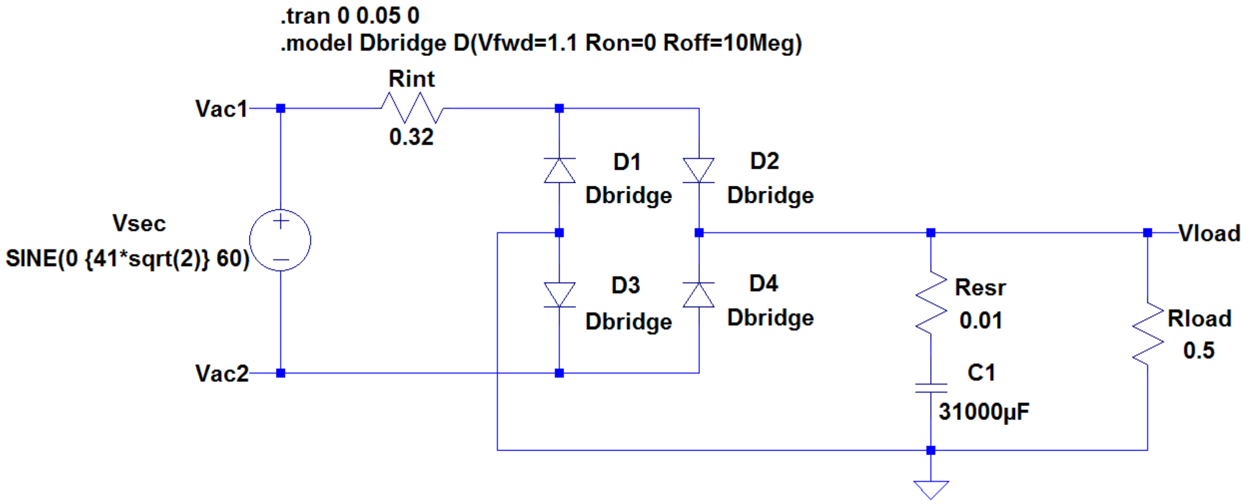
The following graph shows the results of the simulation. The black trace is the driving voltage. The red trace is the voltage drop over the load. Everything looks good.



Do not be surprised to see that the peak voltage applied to the workpiece is a lot more than two volts less than the peak voltage coming from the secondary winding. The peak voltage of the secondary voltage is $\sqrt{2} \times 41 = 58.0V$. Two diodes reduce this by $2.2V$, to $55.8V$. What is left is shared by the load resistance (0.5Ω) and the internal resistance of the transformer (0.32Ω). The two resistances share the voltage and power, and the load only gets $0.5/(0.5 + 0.32) = 61.0\%$ of it. 61.0% of $55.8V$ is $34.0V$. That is the peak voltage over the workpiece. Just because the Hobby-Weld is rated to $50A$ does not mean it is very efficient at that current.

An LTSpice model for the secondary circuit – Including regulation

In this section, I will add the regulating capacitor. The capacitor I used during construction is Digikey's part #338-3470-ND. It is a 31,000µF electrolytic capacitor. The ideal capacitance is shown in the following LTSpice schematic as component C1. I have also tried to account for the internal resistance of the capacitor by including 0.010Ω resistor Resr. Let me explain the origin of this resistance.

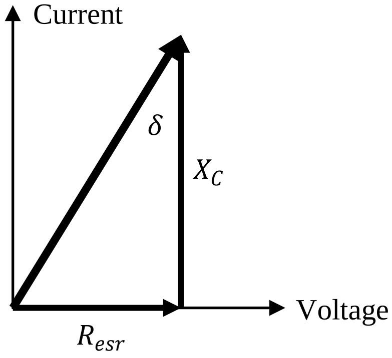


Capacitors are not perfect. One of the flaws of a real capacitor is a small amount of Ohmic resistance. Since it is usually treated as being in series with the ideal capacitance, it is called the capacitor's "equivalent series resistance", or ESR. The datasheet for this capacitor does not quote an ESR. However, a big-value electrolytic capacitor like this would typically have its resistance described as "tangent of loss angle in range 0.15 – 0.25 at 120 Hz". How is this statement to be interpreted?

A capacitor's primary job is to resist the flow of alternating current. This type of AC-resistance is called reactance[3] and is usually represented by the symbol X_C. The reactance depends on the capacitance and on the frequency of the alternating current being resisted. The formula for capacitive reactance, and the value at the specified test frequency, is:

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 120 \times 31{,}000\mu} = 0.043\Omega$$

Consider a normal resistor. Current flows through it in direct proportion to the applied voltage. In a sense, the current is "parallel" to the voltage. Now consider an ideal capacitor. Here, the current "leads" the applied voltage. Current has to flow into the capacitor, charging it up, in order for there to be a voltage drop. In a sense, the current is "perpendicular" to the voltage. The following diagram showing capacitive reactance and normal resistance, plotted on axes of current and voltage at right angles to each other, is used in what is called a phasor analysis.



When the resistance being compared to the capacitive reactance is the capacitor's internal resistance R_{esr}, the "loss" angle is the acute angle δ shown in the figure. The loss angle can be used to compare the strength, or length, of the resistance vector to the strength, or length, of the capacitive reactance vector. From trigonometry, the tangent of the loss angle is defined as:

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[3] Like an inductor, a capacitor resists changes in current. Both the inductor's and capacitor's resistance to such changes are called reactances. In the case of a capacitor, the energy removed from the current flow is stored in an electric field. The stored energy will be returned to the current flow when the electric field shrinks.

$$\tan\delta = \frac{opposite}{adjacent} = \frac{R_{esr}}{X_C}$$
$$\rightarrow R_{esr} = X_C \tan\delta$$

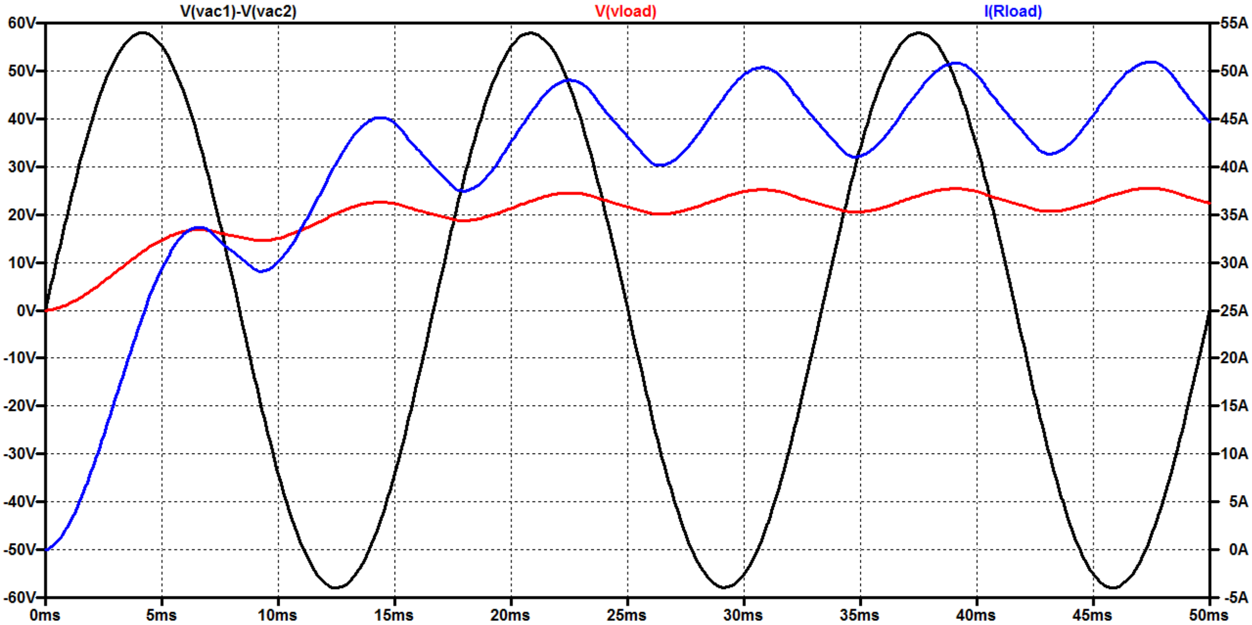
A capacitor's datasheet often gives $\tan\delta$, which is the tangent of the loss angle. It probably will not be greater than 0.25 (and will be quite a bit less for "low-ESR" capacitors). Using this conservative (that is, high) value, we can calculate our capacitor's internal resistance as:

$$R_{esr} = 0.043\Omega \times 0.25 = 0.011\Omega$$

I have used a value of 0.01Ω in the LTSpice model.

The following graph shows the results of the simulation, with the circuit starting from rest at time $t = 0$. In addition to the secondary voltage (rendered in black) and the voltage drop over the load (in red), I have also plotted the current flowing through the load (in blue). Note the following points.

1. It takes about 1½ cycles for the capacitor to charge up after the power is turned on. This is apparent from the upward trend in the output voltage and current at the beginning of the simulation.
2. Once things settle down, the voltage over the workpiece (in red) appears to be sinusoidal and varies between about $20V$ and $26V$. This is what one would expect for an applied sinusoidal voltage with $V_{RMS} = 25V$ followed by two $1.1V$ diode voltage drops.
3. The output current is approximately sinusoidal, with a bit of distortion in the troughs. The current flowing through the workpiece varies between about $41A$ and $51A$.



<u>How did I pick the 31,000µF value for the capacitor?</u>

Generally speaking, a bigger value of capacitance is better at regulating than a smaller value. But, there are two qualifications. When the circuit is first powered up, the capacitor will charge up to the average voltage level. It is possible to pick such a large capacitor that the inrush of current when the circuit is turned on will blow a fuse. Secondly, there is the issue of cost. Big capacitors are not cheap. The 31,000μF capacitor I used cost $40.56, in Canadian dollars. Bigger ones cost even more.

I started by figuring out how much work I wanted the capacitor to do. By "work", I actually mean physical work, measured in Joules.

When $25V$ (all numbers here can be interpreted as being RMS values or DC values) is applied to the workpiece and $50A$ flows through it, the power being consumed, and converted into heat, is:

$$Power = voltage \times current = 25V \times 50A = 1{,}250\ Watts$$

A "Watt" is the consumption of one Joule of energy every second. So, at the design operating point, we are looking at providing $1{,}250$ Joules of energy to the workpiece every second.

Now, our source of energy is the secondary winding of the transformer, which generates alternating current at a frequency of $60\ Hz$, or 60 cycles every second. After the bridge rectifier flips the negative half-cycles into positive half-cycles, there will be a train of 120 positive pulses every second. Each positive pulse will last for $1/120 = 0.0083$ seconds.

If we are to deliver $1{,}250$ Joules of energy in one second, we must deliver $1{,}250/120 = 10.4$ Joules of energy during each positive pulse.

Now, let's look at how much electrical energy is stored inside the capacitor[4]. The energy E stored inside a capacitor is proportional to its capacitance and to the square of the voltage to which it is charged. The formula is this:

$$E = \frac{1}{2}CV^2$$

It might not be obvious yet, but we now have all the tools we need to pick a capacitor. I will set the following two design requirements.

1. We need to send 10.4 Joules of energy to the workpiece during every positive pulse. To smooth out the extremes during the positive pulses, the capacitor must be able to absorb and release energy in this order of magnitude. Suppose I say that the capacitor should be able to absorb and release one Joule of energy, which is about 10% of the energy flow.
2. Suppose I also say that I want the voltage drop over the capacitor to change a maximum of 10% when it absorbs or releases this one Joule of energy.

Here is how we implement these design requirements. Let V_{rms} be the RMS voltage. I will use the symbol E_{rms} for the energy stored in the capacitor at this voltage. When we add one Joule of energy to the capacitor, so that its total energy is $E_{rms} + 1$, we want the voltage to be $1.1V_{rms}$. Similarly, when we remove one Joule of energy from the capacitor, so that its total energy is $E_{rms} - 1$, we want the voltage to be $0.9V_{rms}$. The energy-voltage relationship at these two extreme conditions can be written as:

$$E_{rms} + 1 = \frac{1}{2}C(1.1V_{rms})^2$$
$$E_{rms} - 1 = \frac{1}{2}C(0.9V_{rms})^2$$

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[4] The energy is stored in an electric field between the negative charge on one plate and the positive charge on the other. The attraction actually causes the two plates inside the capacitors to pull on each other.

If we subtract the second equation from the first, we get:

$$\begin{aligned} & 2 = \tfrac{1}{2}C[(1.1V_{rms})^2 - (0.9V_{rms})^2] \\ \rightarrow \quad & 4 = C(1.21 - 0.81)V_{rms}^2 \\ \rightarrow \quad & C = \frac{10}{V_{rms}^2} \end{aligned}$$

Since our design output voltage is $V_{rms} = 25V$, the required capacitance is:

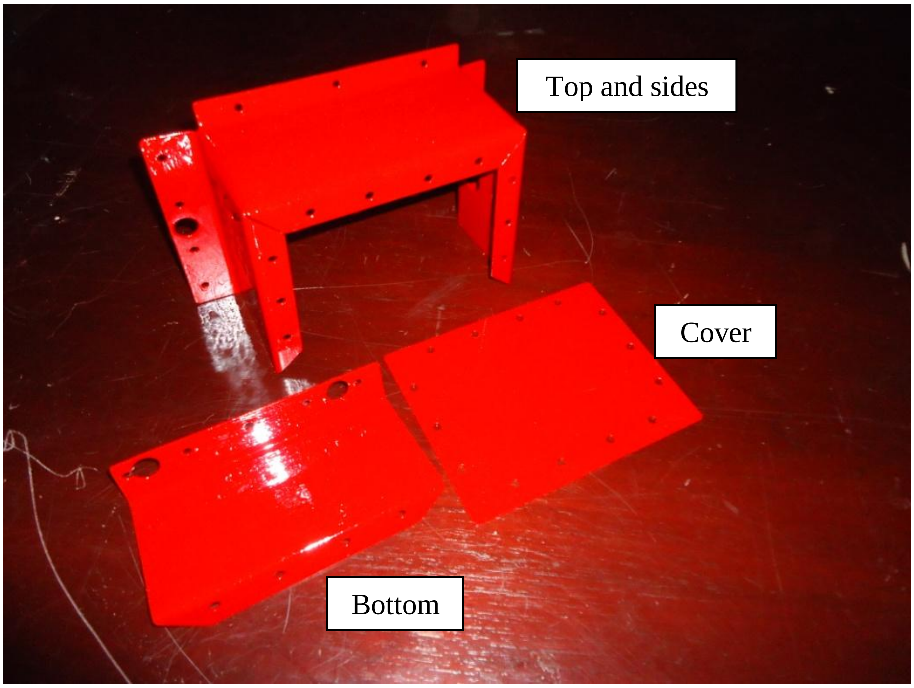
$$C = \frac{10}{25^2} = 0.016 \text{ Farad} = 16{,}000\mu\text{F}$$

Large capacitors are difficult to manufacture to an exact capacitance. $\pm 20\%$ is the typical uncertainty. To be safer than sorrier, I looked for a capacitance a little bit bigger than $16{,}000\mu$F. The one I selected from Digikey's selection or products happened to be $31{,}000\mu$F, but it had a couple of other things I needed. It is rated to $50V$, so it can withstand the open-circuit voltage. And, it has screw terminals, so the connecting cables do not need to be soldered.

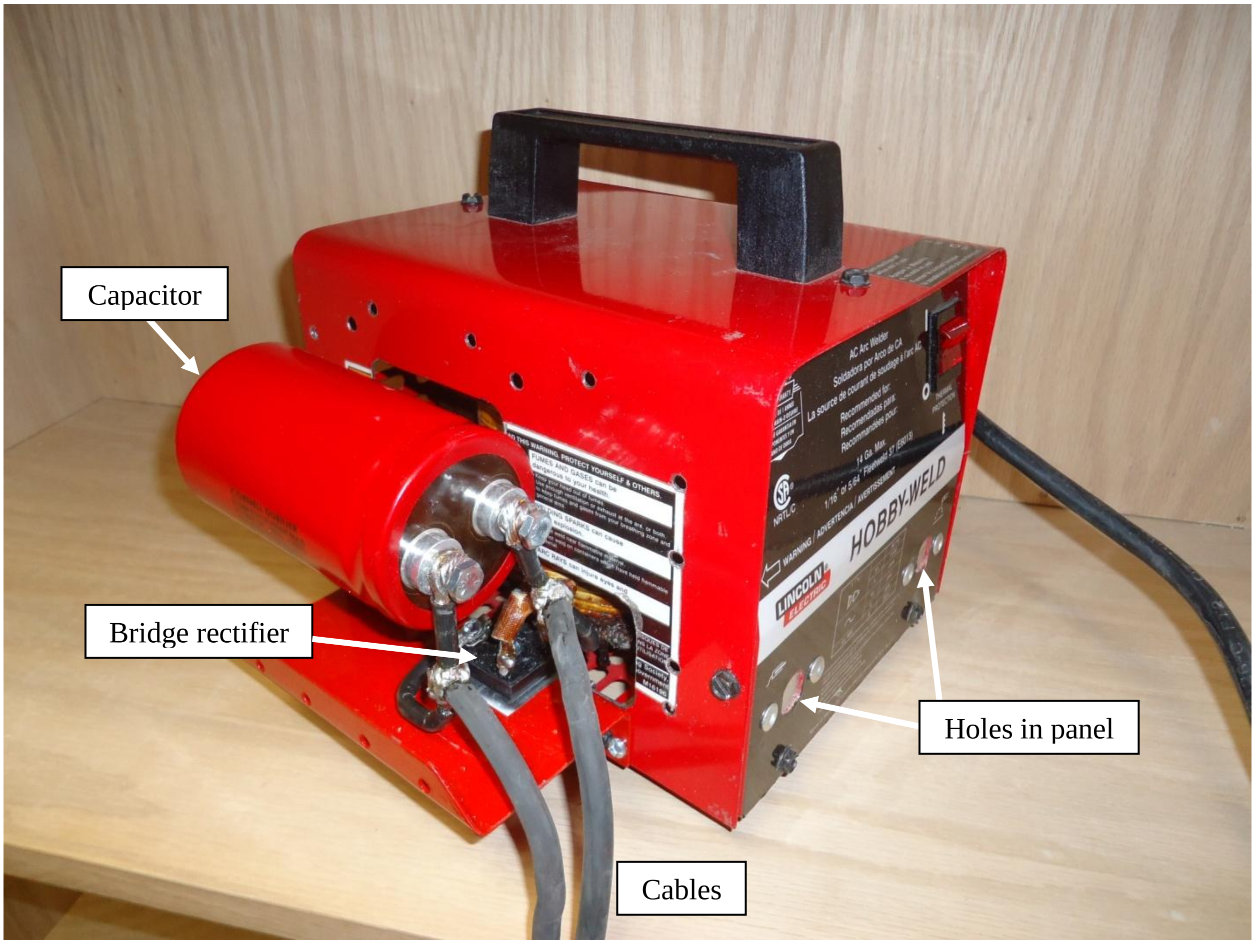
Construction

I mounted the bridge rectifier and the capacitor on the outside of the left-hand side of the unit, as viewed from the front panel. The following picture shows the hole I cut in the left side to allow wiring and heat to flow between the new external compartment and the interior of the unit.

To make a box for the new components, I cut and bent some sheet metal into three pieces. I painted them with red Tremclad paint, which seems to be a perfect match for Lincoln red.



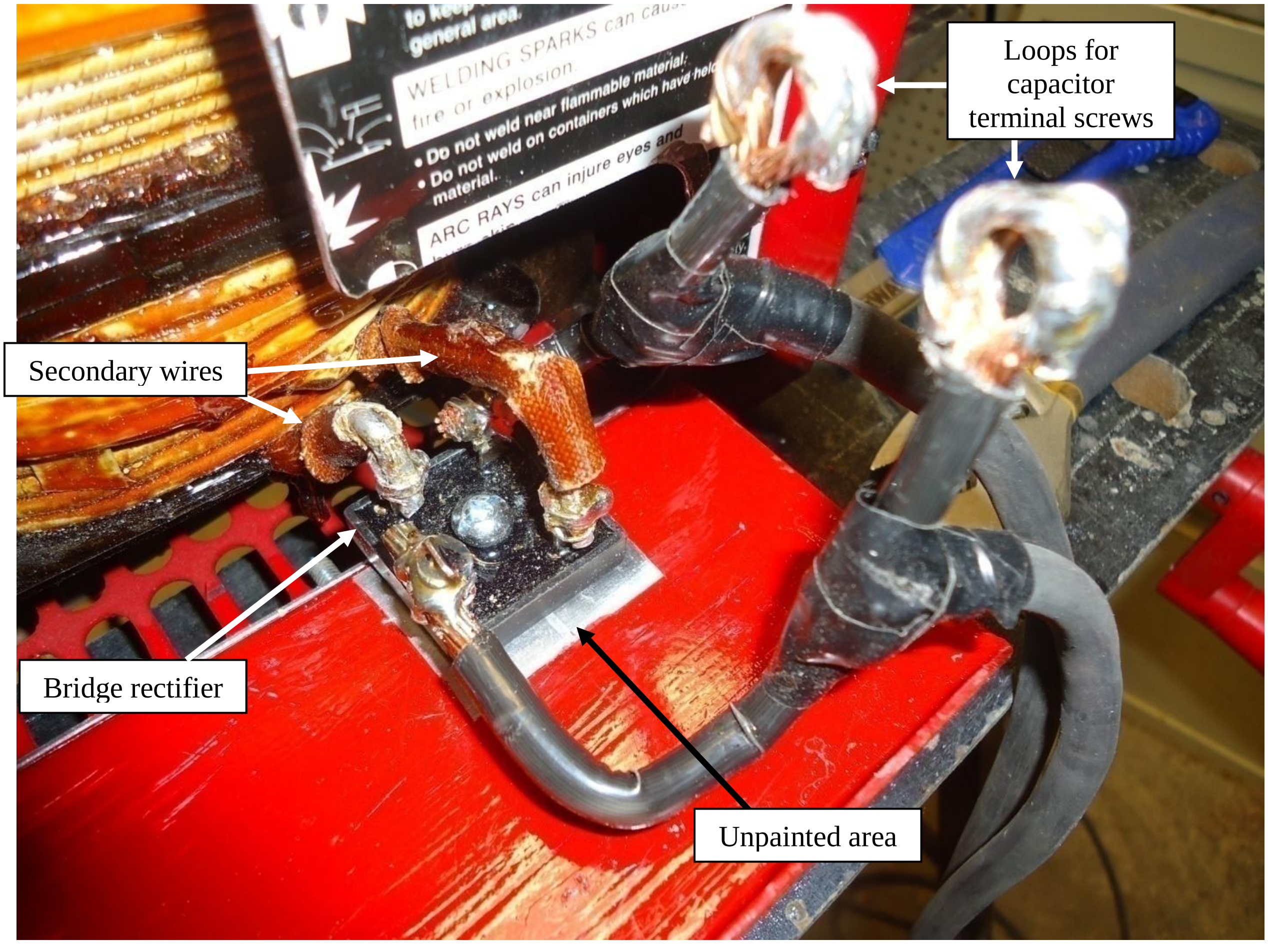
The following picture shows the left side with the capacitor and bridge rectifier now wired into position.



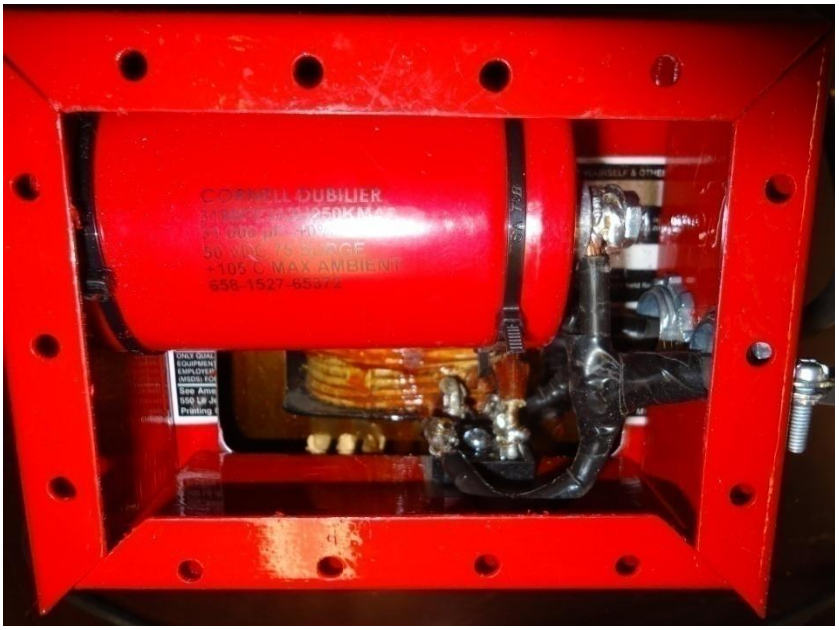
The bridge rectifier has a flat base and is bolted to the bottom of the new external enclosure. The top, sides and cover of the new enclosure are not shown in the picture above. The bridge rectifier was mounted on the bottom plate to be as close as possible to the point where the wires of the secondary winding exit from the transformer. The capacitor is mounted above the bridge rectifier and will be (not shown here) secured to the left side of the unit using cable ties.

The cables to the stick handle and the ground clamp are connected directly to the vertical wires from the bridge rectifier to the capacitor's terminals. On the original unit, the cables came out through holes near the bottom of the front panel. To cover these holes, I pop-riveted an aluminum plate to the inside of the front panel.

The following picture is a detail looking down onto the bridge rectifier before the capacitor was mounted above it. Let me point out a couple of things. The bridge rectifier is a relatively flat square box. Its four terminals rise from the four corners. It is bolted to the bottom of the new external enclosure using a bolt through the central axis. It is important that the rectifier be connected tightly to the metal bottom. This is to improve the flow of heat from the rectifier into the surrounding metal case. When in operation, $50A$ of current flow through two of the rectifier's diodes. Each diode drops $1.1V$, so each diode must dissipate $50A \times 1.1V = 55$ Watts of power. In total, the bridge rectifier will be dissipating 110 Watts of power. That's a lot of power from a little parallelepiped of plastic to deal with. To improve the flow of heat away from the device, it helps to remove the paint in the area where the rectifier is mounted. The paint acts like an insulator. It further improves the heat flow to place a bit of silicone compound between the rectifier and the bottom. Silicone is a conductor of heat. It also fills some of the microscopic holes which exist because metallic surfaces are not truly flat, but only to the naked eye.



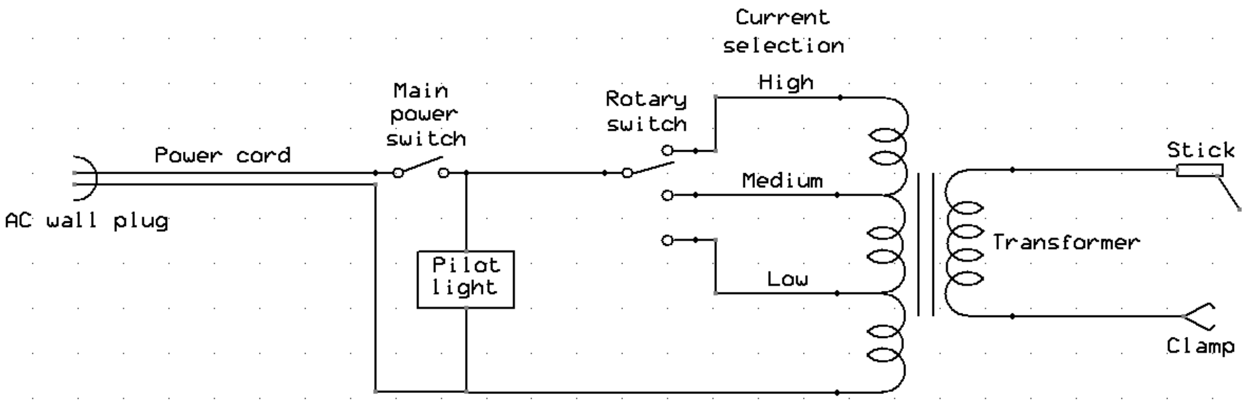
The following picture is the view from the side into the new external enclosure before the cover is pop-riveted into place.



The ability to adjust current

So far, I have dealt only with the first half of the project. The alternating current has been converted, not just into rectified DC, but into regulated DC. But the unit still can only weld at one setting, all out. In this section, I will describe a rudimentary way to adjust the amount of heat that is delivered to the workpiece.

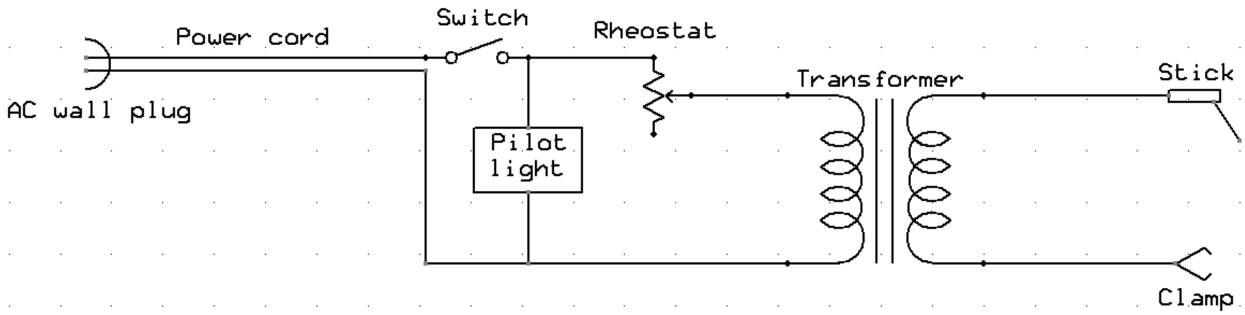
A good store-bought welder will have a rotary switch on the front panel which allows the user to adjust the power setting. Typically, the various switch settings are labelled with the maximum current which the particular setting will deliver. Often, the switch determines which tap on the primary coil receives the incoming AC power from the wall outlet or the generator. The operation of the rotary switch can be described with the help of the following snippet of schematic.



The circuit will have a main power switch and, possibly, a pilot light like the Hobby-Weld. I have shown a rotary switch with three settings. The setting determines how many turns in the primary coil are engaged. In the topmost setting (as per the schematic) all of the turns of the primary winding are powered. In this setting, the transformer will have its lowest "turns ratio", which is the number of turns in the secondary winding divided by the number of turns in the primary winding. The secondary winding will develop its lowest voltage drop but, conversely, will be able to deliver the maximum amount of current.

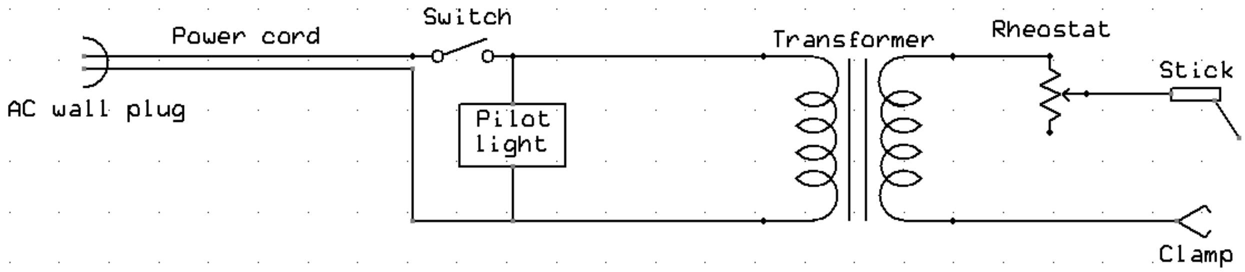
This approach means that there have to be multiple connection points, or "taps", on the primary winding. Adding taps when winding the primary is not hard. What is hard, though, is designing a transformer which will be efficient (not losing too much electrical power into heat) over a wide turns ratio. This problem, of dealing with a wide scaling range, is not avoided if the rotary switch is used on the secondary winding instead of the primary winding.

A slightly different approach can be used. It involves controlling the voltage of the alternating current input using a big potentiometer, called a "rheostat" when used this way. The following snippet of schematic shows the essentials of this scheme.



The rheostat is simply a resistor wired in series with the primary winding. It burns off some of the power, reducing the voltage drop which is applied to the primary winding. This will reduce the voltage and current at the workpiece. But, it does not avoid the problem of inefficiency in the transformer, which was likely designed for standard mains, either $120V$ or $220V$. Furthermore, the rheostat must be big, and very expensive, to accommodate the power levels in play here. The heart of the problem is that the rheostat must have a very, very low resistance. Its total resistance must be of the same order as the resistance of the load, which is to say, a fraction of an Ohm. However, if one has a suitable rheostat lying around, it can easily be put to work this way, and does not require modifying the welder.

A similar approach is to put the rheostat to work in the secondary circuit, as shown in the following schematic. The requirements for the rheostat are as demanding here as they are when the rheostat is in the primary circuit. Arguably, they are even worse. The current flowing through the primary circuit will not be much more than $15A$ while in the secondary it is designed to be $50A$. (If one has enough money to buy a rheostat that will work here, then one has enough money to buy another welder altogether.)



On the other hand, there is a very easy way to add a variable amount of resistance to the secondary circuit. A couple of hanks of long wire will do the trick.

Since I ended up using AWG #12 wire, I will use its parameters in the following discussion. #12-gauge wire is a little bit heavier than usual. Houses are usually wired using #14-gauge. (Remember that higher gauge numbers correspond to thinner wire.) All we need to do is cut a length of wire which has a suitable resistance.

One might ask: why is heavy wire necessary? That is a good question. Before I had actually tried some wire, I did not have a good answer. Now that I have experimented, I have a better answer. Here it is.

Thin wire has a higher resistance per unit length than thick wire. One can obtain any desired resistance, say, one-half Ohm, using a short length of thin wire or a long length of thick wire. Both pieces of wire will do exactly the same thing when they are placed in series in the secondary circuit. They will drop the same voltage, pass the same amount of current and burn off the same amount of heat. The only difference is how hot the piece of wire will become. The shorter, thinner wire will dissipate more heat per foot of length than the longer, thicker wire. I do not have any innate feeling for how hot such-and-such number of Watts per meter actually feels like when one grabs the hank of wire. I have found through use that #12 wire gets only slightly warm to touch when I am welding. However, I now believe that #14-gauge wire would have been perfectly satisfactory for this purpose.

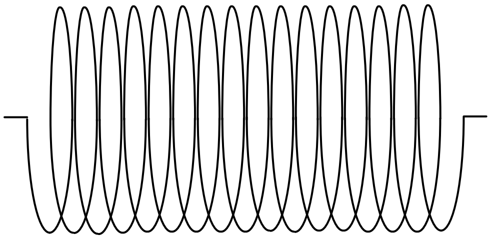
What is a suitable resistance? That also is a question which is easier to answer after having tried a few different lengths. The following table sets out the lengths of the three hanks of wire I found to be most useful. The resistance of AWG #12 wire is given as 1.588 Ohms per thousand feet. I have used this factor in the table to calculate the total resistance of each hank.

Length of wire	**Resistance**	**Colour**
31 ft 6 in	0.05 Ω	Black
63 feet	0.10 Ω	Red
126 feet	0.20 Ω	Blue

The colour will not be relevant for you. It happened that I had access to a number of spools of #12 wire with different colours of insulation. I cut the three lengths from different colours.

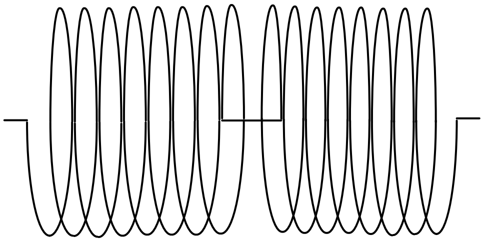
There is one matter to be aware of. One's natural tendency is to take each piece of wire and coil it up into a hank a foot or so in diameter. I strongly recommend that the resulting hanks be divided into two halves and that the two halves be taped to each other in reverse directions. The following diagram shows what I recommend.

NO



All turns clockwise

YES



Half of the turns clockwise

Half of the turns counter-clockwise

Ten or twenty circular turns of wire has a fair bit of inductance, easily up into tens of milli-Henries. When it is placed in parallel with the regulating capacitor, there is the possibility that an oscillation of energy between the inductor and the capacitor will arise. The resistance in the workpiece will tend to damp out any oscillations. Even so, it is worthwhile to take a look at the "resonant" frequency at which the circular hank of wire and the capacitor are best suited to exchange energy. The resonant frequency of an L-C circuit is given by:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

If the hank of wire has an inductance of $10mH$, it will resonate with the $31{,}000\mu F$ capacitor at a frequency of:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.01 \times 0.031}} = 9.0\ Hz$$

This is getting awfully close to the $60\ Hz$ mains frequency. A shorter piece of wire or a different size of hank and we could be flirting with a nasty oscillation.

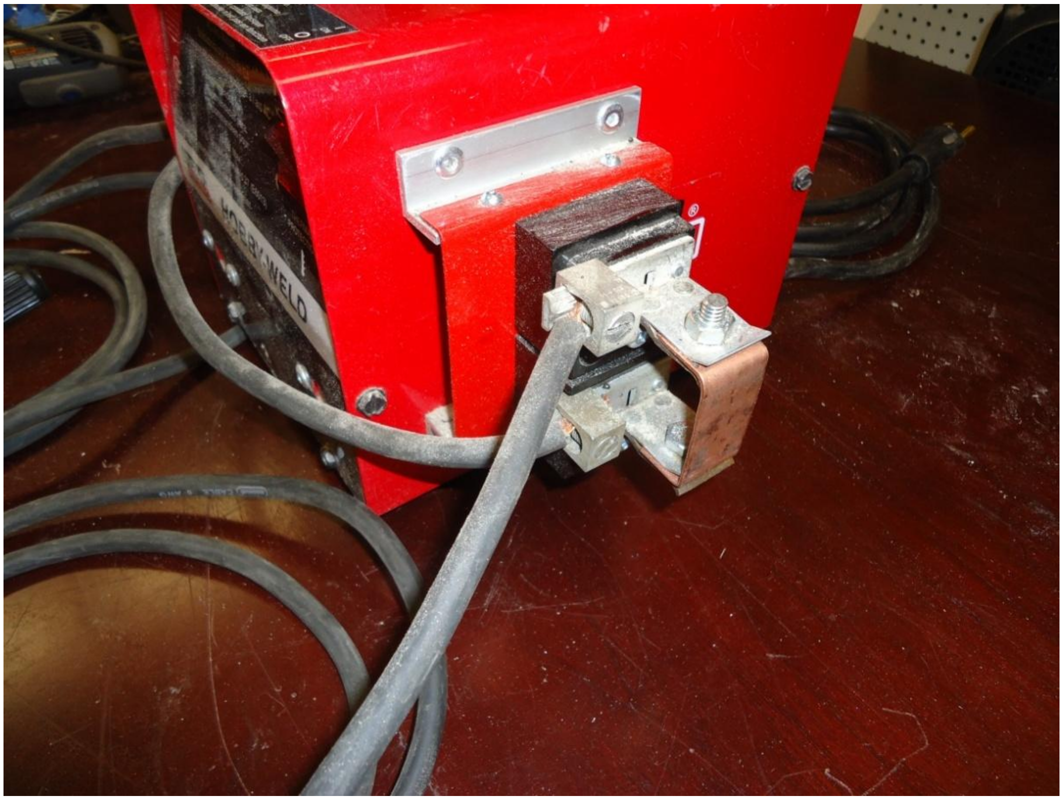
The way to deal with this possibility is to reverse the direction of two halves of the coil. The magnetic field generated by the current flowing through one half will be almost entirely offset by the magnetic field generated by the current flowing through the other half. For coils of wire wound by hand, the offset will never be perfect. But, it will reduce the inductance by a couple of orders of magnitude, so the resonant frequency is shifted up and away from the mains frequency.

Construction

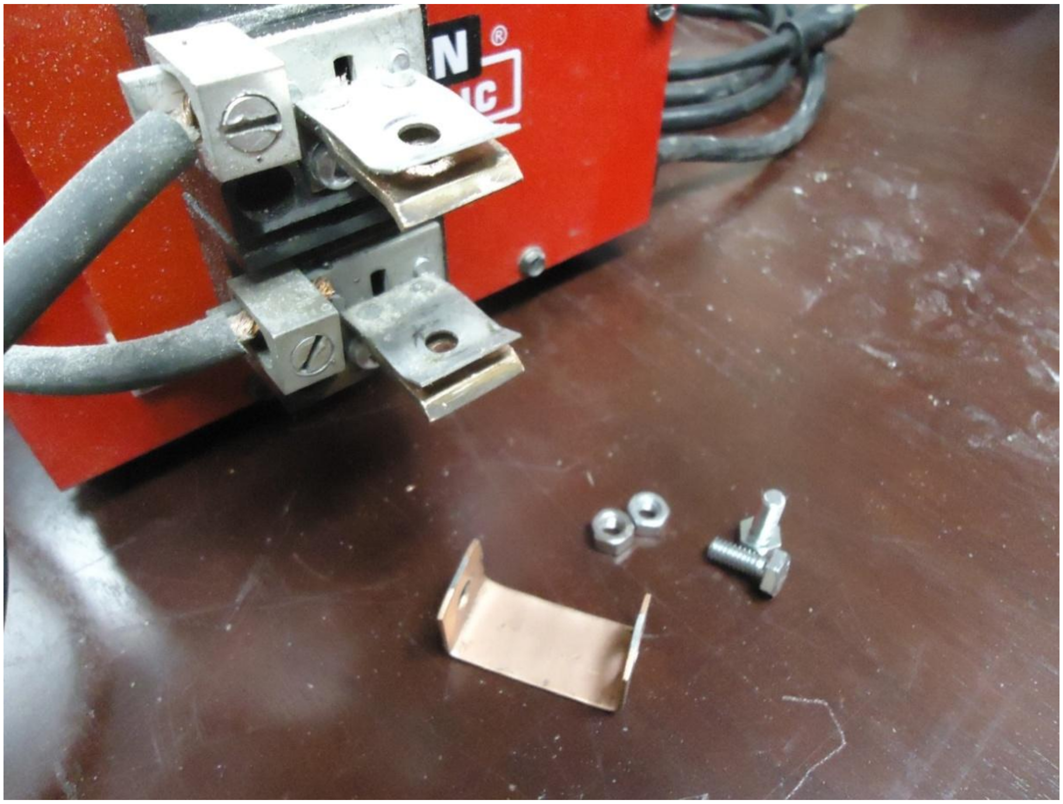
It is not difficult to make a hank of wire. It is more difficult to figure out a way to include the hank in the secondary circuit. Some ingenuity is called for. I was lucky and had access to an old electrical panel. One of the fittings inside it was a mounting block for heavy-duty power fuses (100 Amp fuses). It was perfect. I mounted it on the right-hand side of the unit, where it could balance some of the lopsided weight of the rectifier-capacitor enclosure on the other side. The following picture shows the modified Hobby-Weld from the front.

Connector for external resistance

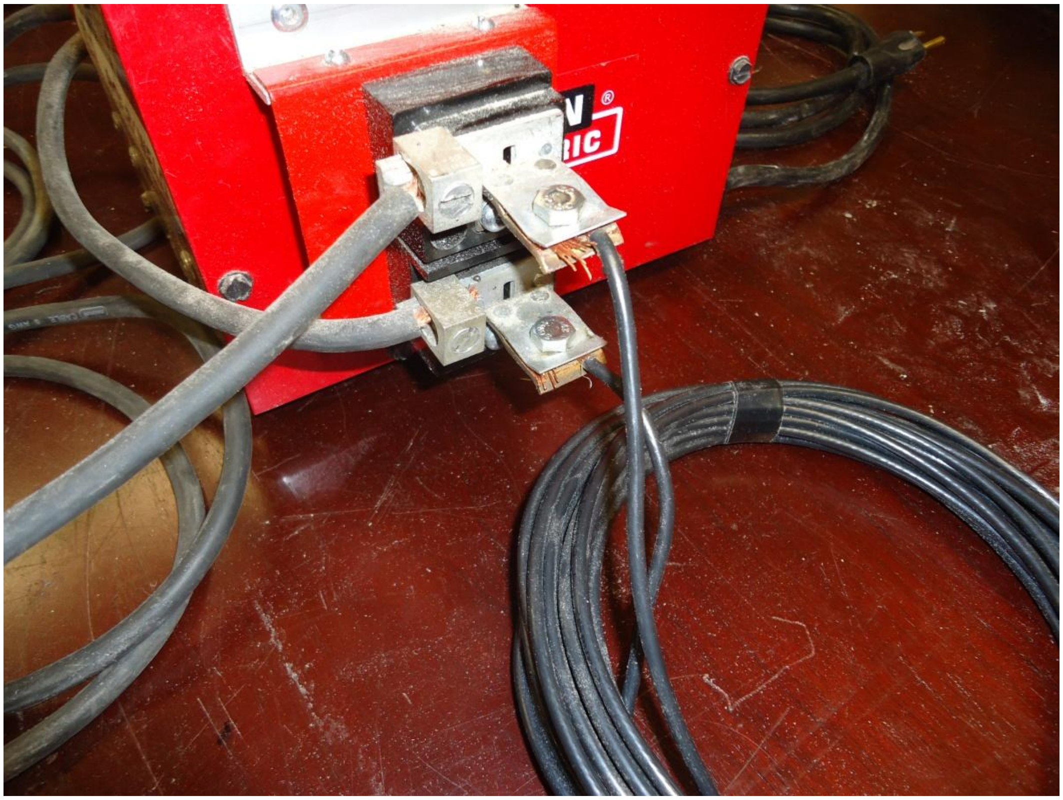
The following picture shows the connector in more detail.



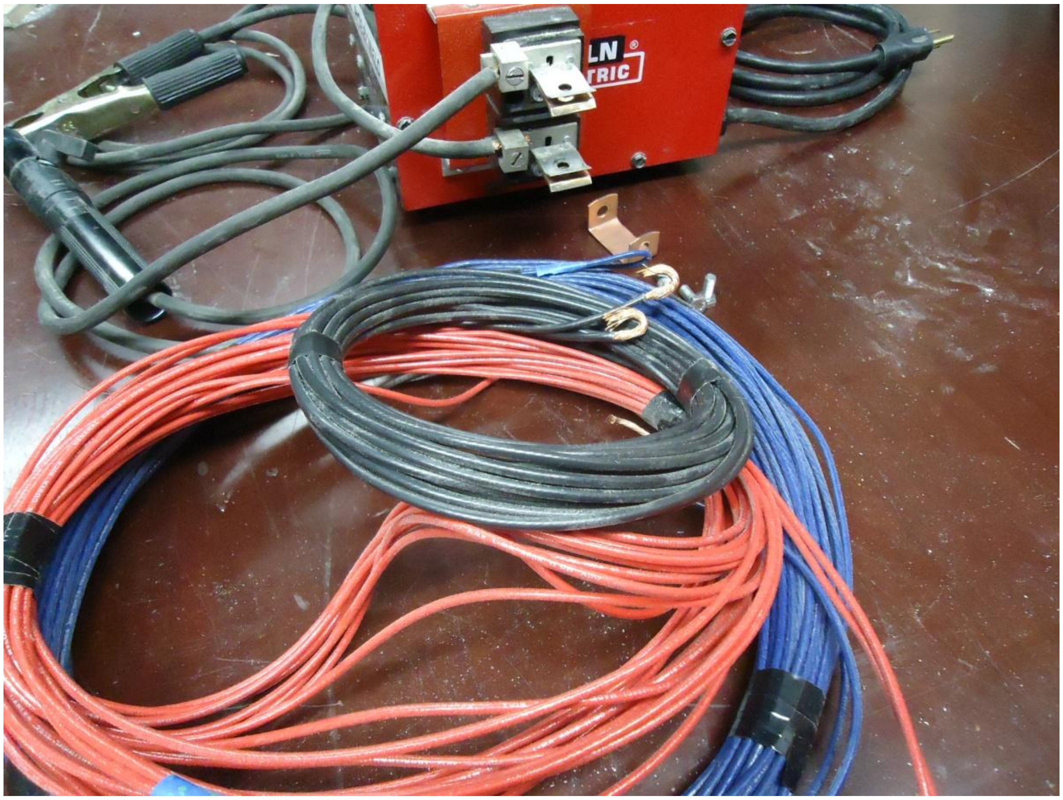
The two terminals of the connector are located one above the other. Each terminal has a substantial bolt. The resistor shown in the figure is a heavy strap of copper bend into a U-shape. It is a zero resistance “jumper”, or “shunt”. The following picture shows the connector with the shunt removed. Each terminal has two plates, which are drawn together by a bolt, ideal for holding wire ends.



The following picture shows the connector with the black resistance coil (0.05Ω) connected.



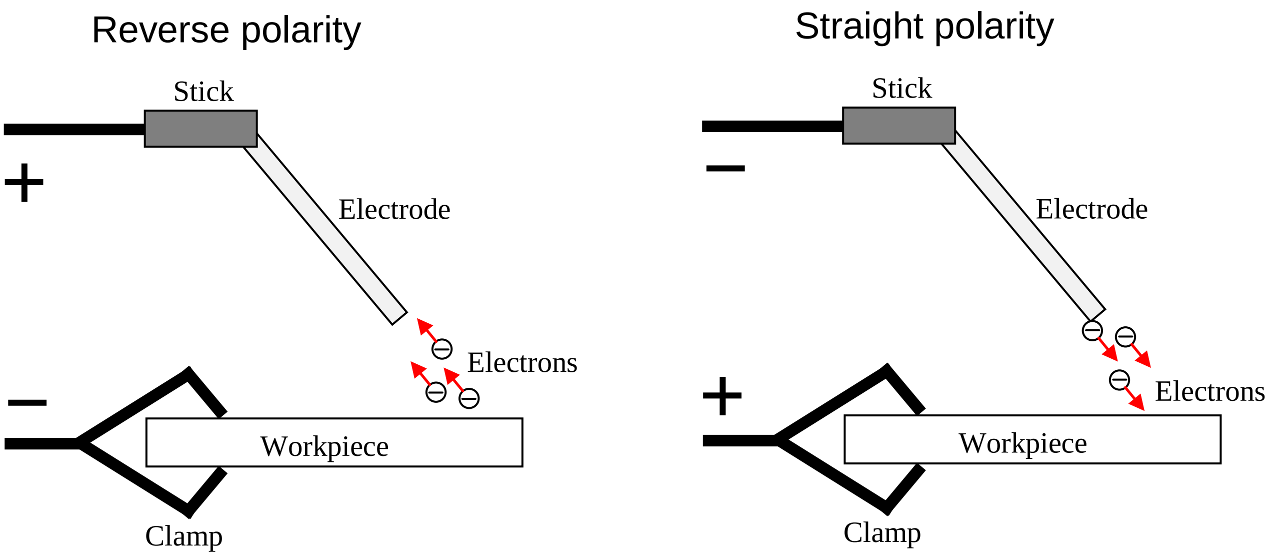
Lastly, the following picture shows the three resistance coils, and the shunt.



<u>The effect of polarity</u>

In this section, I will discuss the polarity of the connection from the power supply to the stick and the ground clamp. An alternating current flows back-and-forth, so the concept of polarity does not apply to an AC welder. Direct current, on the other hand, whether it is only rectified or regulated as well, flows in one direction. Current is said to flow from a higher voltage terminal towards a lower voltage terminal. In all of the schematics above, I wired things up so the current flows through the workpiece <u>from</u> the electrode <u>to</u> the clamp. I could just as well have shown the reverse, and wired things up so the current flows through the workpiece from the <u>clamp</u> to the <u>electrode</u>. From an electrical point-of-view, the two arrangements are identical. If the stick, workpiece and clamp can be treated as discrete "normal" resistances, it does not matter which way the current flows through them.

In practice, the direction of the current flow does matter, and it matters a lot. To begin with, I have shown in the following diagram the two possibilities. On the left is the arrangement I have used above, with the stick at the positive end. The clamp is at the negative, or so-called "ground" end. In fact, I have referred to the clamp a couple of times as the "ground clamp". Although this is how electricians would probably wire up the circuit, welders call it "Reverse Polarity". "Straight Polarity", shown on the right, has the clamp at the higher potential. Go figure.



One talks about current flowing from a higher potential/voltage to a lower potential/voltage as if it consisted of little bits of positive charge. In reality, it is the movement of negatively-charged electrons which constitutes current flowing through a metal. The electrons actually travel in the opposite direction from the "current". Inside the plasma, which is the region of charged particles between the end of the electrode and the workpiece, the electrons move in the direction shown by the red arrows in the diagram. In Reverse Polarity, electrons are ripped off the surface of the workpiece and fly towards the end of the electrode. In Straight Polarity, electrons are ripped off the tip of the electrode and fly towards the surface of the workpiece.

For a couple of reasons, what happens in the two cases is different. With a few exceptions, Reverse Polarity results in deeper penetration into the workpiece. Electrons are pulled from a smaller surface area on the workpiece. Straight Polarity results in faster melting of the electrode and spreads the deposited metal over a bigger area. The result is shallower penetration into the workpiece.

I mentioned exceptions. Some electrodes are covered with a flux which is designed for use in only one polarity. For these electrodes, using the correct polarity over-rides consideration of deeper versus shallower.

Since I do general welding only, I wired the Hobby-Weld for Reverse Polarity. The polarity can still be changed, of course, by switching the cables to which the stick handle and clamp are attached. This takes some unscrewing and re-screwing but it can be done. A good store-bought DC welder, on the other hand, will probably have a rotary switch on the face plate which allows the selection to be made quickly.

Jim Hawley
July 2016

(An e-mail setting out errors or omissions would be appreciated.)