Here is Chapter 5j of the *Musical Engineer's Handbook* and four App Notes on power supply design. The notion of having App Notes was born from having to answer questions on power supplies so often from little storefront just off the Cornell U. Campus back in 1976. It seemed easier to just write it up and offer then for a dime. From these, the notion of launching into the publication of a more general (more general than just music synthesizers) evolved. It seems that power supplies are still needed – in all these years ICs have not learned how to work unfed!

CHAPTER 5J

POWER SUPPLY DESIGN

CONTENTS:

INTRODUCTION

Power supplies often seem like an imposition - most circuits need one, and they can be both bulky and expensive. Furthermore, once one is built, you still have to build something else to get something that does something interesting. A small device that you may want to carry around needs its own supply, and even if you have a central supply back in your lab with amps to spare, it won't help on the road. At some point, the user has to decide how he wants to physically locate supplies: one central supply or a supply in each piece of equipment.

The basic procedure for power supply design is to first build an unregulated supply and then add a regulator. In general, we will find that it is quite easy to do both. The unregulated supply involves the selection of a transformer, a rectifier, and a filter capacitor. Integrated circuit voltage regulators are then applied to obtain the proper voltage from the unregulated supply. Usually, a few external capacitors are added to stabilize the regulator, and finally various protective devices such as current limiting and overvoltage protection can be added if these features are desired and are not available as part of the normal function of the IC regulator. The first step in the design is to determine the power requirements of the circuits to be powered.

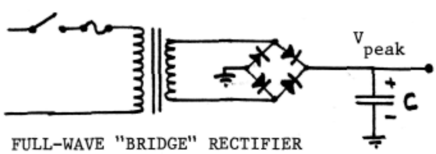
DETERMINING POWER REQUIREMENTS

The basic supply requirements are ±15 volts bipolar for op-amps and other linear IC's, and +5 volts for TTL and other digital circuits. As CMOS digital IC's come into wider use, the +5 supply may not be needed, as CMOS can run on voltages from +3 to +18. Other supply voltages may be called for in some designs and must be considered carefully. Four points in this regard should be noted: (1) Power supplies for op-amps are sometimes indicated as ±12 or ±13, but most op-amps will work on ±15. (2) Common positive voltages other than +15 and +5 are +9, +12, +18, and +24. Of these, +12 and +18 devices will often run on +15. The +12 and +9 voltages can also be supplied from +15 by using a Zener diode to drop the excess voltage. (3) A bipolar supply of +12 and -6 was used at one time but is now uncommon. (4) Most digital IC's will run on +5 volts (TTL, DTL, and CMOS). RTL will also work on +5, but it is a good idea to drop the +5 to about 3.8 volts by two series silicon diodes.

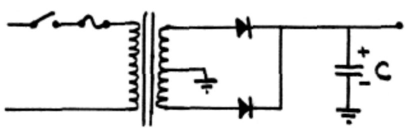
Determining the required current is more difficult. Thus, it is necessary to make some rough estimates and then make sure there is plenty of extra available. Often times you will be adding on other circuits later anyway. Also, designing a regulator for more current than is usually drawn will assure that it will run cooler. With some devices, it is better to limit the current at just slightly more than the device requires when functioning properly. Any excess current will shut down the regulator. In most cases however, it is more convenient to just use a supply with current to spare. When estimating current needs, the following rules of thumb can be used: (1) Allow 2 ma for each op-amp and add to this the current corresponding to +15 volts through the resistance connected to the output of the op-amp (if any). For example, if there is a 4.7k load resistor on the op-amp, when the output is at either +15 or -15, about 3 ma will be delivered to the load. Add to this the 2 ma for the op-amp itself, and you get a total requirement of 5 ma. (2) For TTL, estimate 10 ma for each package of gates, and up to 60 ma for a more complicated TTL package. Consult data books or the TTL Cookbook if you need accurate figures. For slow speed (including audio), CMOS requires very little current and need not be considered. When it gets right down to selecting a regulator, often times the choice is between a low current version (around 100 ma) and a high current version (around 1 amp). Careful consideration of the current requirements is therefore necessary only when the rough estimates come close to one of these limits.

THE BASIC UNREGULATED SUPPLY

As a first step, a transformer can be selected. The transformer should have a standard AC primary and the secondary voltage should be selected to be the same or slightly higher than the output voltage of the supply you are trying to design (e.g., an 18 volt transformer will work for a 15v supply). The current rating of the secondary should be at least as high as the peak current of the supply. The transformer may also be one of twice the voltage with a center tap (e.g., a 12.6V transformer center tapped for a 5V supply). In fact, there are a couple of advantages to this as we shall see. We then proceed to set up an appropriate rectifier circuit using diodes. It is best here to use a full-wave rectifier, not a half-wave, as this will mean that we can use less filtering. There are two choices of full-wave rectifiers, depending on whether we have a center tapped transformer or not.



FULL-WAVE "BRIDGE" RECTIFIER



CENTER TAPPED FULL-WAVE RECTIFIER

Given the choice, the center tapped transformer method is preferred for several reasons: (1) It uses only two diodes (which is not to say the two diodes saved will save you the possible expense of the center tapped transformer). (2) Since there is a voltage drop across any real diode, there is only one such drop for the center tapped transformer, two for the bridge rectifier case. (3) Since only half the transformer and only one diode are used at any one time, the current ratings of these two can be halved. (4) The setup is easily expanded to give the corresponding negative voltage for bipolar supplies as we shall see.

What is the value of V_{peak}? The first thing to realize is that the voltage rating of the transformer is the RMS value, so the actual AC voltage amplitude out is $\sqrt{2} = 1.414...$ times the RMS value. For example, a 6.3 volt filament transformer has an output amplitude of 8.9 volts. This voltage is applied across a diode to the capacitor C. The diode drop is often thought to be 0.6 volts for a silicon diode, but since the diode conducts heavily, it may effectively be higher. A good safe value is twice the standard or 1.2 volts. Next we observe that the transformer voltage charges the capacitor through the diode, and the capacitor voltage follows the transformer voltage minus 1.2 volts as it rises. When the transformer voltage starts to fall, the diode is back biased and capacitor holds the highest positive value it had. Thus, we see that the peak voltage is:

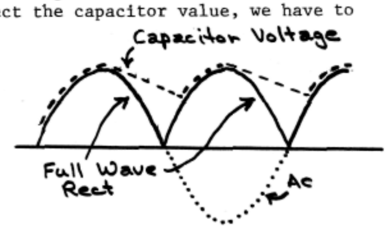
$$V_{peak} \simeq 1.4(V_{RMS}/2) - 1.2 \quad \text{[center tapped transformer]}$$

$$V_{peak} \simeq 1.4(V_{RMS}) - 2.4 \quad \text{[full wave bridge setup]}$$

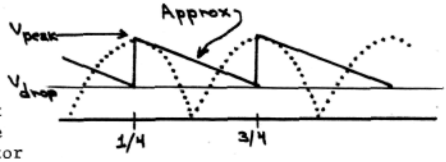
where V_{RMS} is the advertized transformer voltage, and 1.4 is taken as a close enough approximation to the square root of two.

What diodes should be used? In most cases, a diode rated at one amp 100 volts will do (or a higher rating on one or both values). In the case of the center tapped transformer setup, 1/2 amp averages through each diode for a 1 amp supply. The reverse voltage rating of the diode (i.e., the advertized voltage rating) should be at least twice the value of V_{peak}. Note that the maximum voltage across the diode occurs when it is holding back V_{peak} and the transformer voltage is at its negative maximum, and this adds up to about twice V_{peak}. For the highest supply voltages we are considering here (15 volts), the maximum allowable value of V_{peak} is determined by the maximum allowable input voltage to the regulator. In most cases, this value for an IC regulato is 30 - 35 volts. Thus, the diodes should be rated at at least 70 volts, and 100 volts is better. The diodes should be mounted with short leads, but slightly away from any mounting surface. The short leads should conduct heat away from the diodes to a large metal tab on a PC board if possible as this will aid in cooling.

How should the capacitor C be determined? First of all, the voltage rating should of course be greater than V_{peak}. Secondly, the capacitor should have a value as large as is necessary, but not much larger - contrary to the design of unregulated supplies where you usually make it as large as possible. In the case of a regulator, making the capacitor too large will just cause the regulator to run hotter and will not improve anything. To understand how to select the capacitor value, we have to consider how the transformer and diodes charge the capacitor, and what the capacitor voltage looks like when a current is being drawn. We will find that it looks something like the diagram at the right. The transformer voltage first charges the capacitor up during the first quarter of the AC cycle, and then drops out, leaving the capacitor to supply any current to the load. During the third



quarter of the AC cycle, the transformer again charges the capacitor up to V_{peak}. Next recall that the charge on a capacitor is related to the capacitance and the voltage by $Q = C \cdot V$, and current is the time rate of change of charge; $I = dQ/dt = C(dV/dt)$. This tells us that a constant current will discharge the capacitor along a straight line. We can now approximate the actual discharge as shown at the right, bearing in mind that we are playing it safe since the capacitor will actually start recharging before the actual 3/4 point. In IC regulators, there is a minimum input voltage called the dropout voltage below which the output voltage of the regulator can not be maintained. The capacitor voltage must therefore remain above the dropout voltage at all times. The dropout voltage is typically 2 to 3 volts above the regulator's rated output voltage. We can now develop a simple formula for the capacitor size.



The linear discharge section in the diagram above runs from V_{peak} to V_{drop} in a time of 1/120 of a second. Thus we can set a value for the maximum allowable ripple voltage on the capacitor: $V_{ra} = V_{peak} - V_{drop}$. This value V_{ra} is taken to be ΔV while the time of 1/120 of a second is taken to be ΔT. Since we are using an approximation that is a linear discharge, we can replace the differentials in $I = C(dV/dt)$ by ΔV and ΔT and arrive at the equation solved for C as:

$$\boxed{C = \frac{I}{120 \cdot V_{ra}}}$$

where: I is the maximum current to be drawn

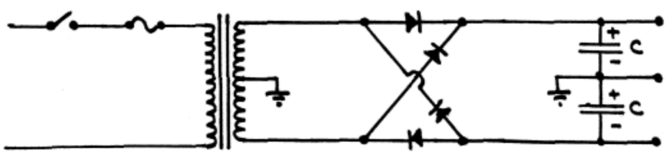
$V_{ra} \simeq V_{peak} - (V_{out} + 3)$

V_{peak} is given on page 5j (3)

EXAMPLES: Suppose you want to make a 1 amp 5 volt supply using the LM309 or a 7800 series regulator and a 12.6 volt filament transformer that is center tapped. The peak voltage on the capacitor is $(6.3 \cdot 1.414) - 1.2$ or 7.7 volts. The 5 volt regulator needs 2 volts above the output or 7 volts minimum. This gives an allowable ripple of only 0.7 volts. For a one amp output, the capacitor is $C = 1/(120 \cdot 0.7)$ or about 12,000 mfd. This is a rather large capacitor, but the supply is useful for several reasons: (1) It is often used as a test bench supply and the current required is well under the maximum. (2) The design was on the conservative side and there may be more peak voltage available, and (3) Having such a low peak voltage means that the supply runs with very low heat dissipation and runs very cool.

In this case, we might have considered the full wave bridge. This would have given a peak voltage of $(12.6 \cdot 1.414) - 2.4$ or about 15.4 volts. The allowable ripple is then $15.4 - 7 = 8.4$ volts. Thus, $C = 1/(120 \cdot 8.4)$ or about 1000 mfd. Here, the capacitor is much smaller, but the regulator will run hotter.

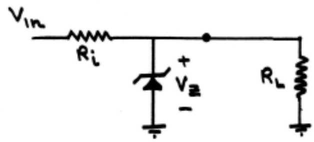
For a bipolar supply, the setup below is used:



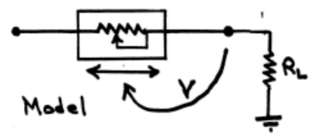
The following points about the bipolar supply should be noted: (1) If we remove the ground connections, this is just a full wave bridge rectifier. (2) It is also really a double sided center tapped transformer setup as well. Two diodes and one capacitor have been added to use the negative transformer voltages as well. We have added just what we would have used in the first place if we wanted a negative supply. (3) The current rating of the transformer must be the same as the output current rating of either polarity, not half the output current rating as would be the case if single polarity supply were used alone. Other calculations remain the same as though the supplies were separate.

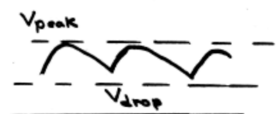
BASIC CONSIDERATIONS FOR REGULATORS

The simplest sort of regulator that can be used is the Zener diode regulator. This can often be used to derive a lower voltage from a standard supply when some odd voltage value is needed. The basic Zener diode regulator is shown at the right. The Zener diode can be thought of as drawing whatever current is necessary so that the excess voltage from the primary source is dropped to the Zener voltage across R_i. If part of the dropping current is drawn by the load, the Zener draws less. Note that the Zener must be prepared to dissipate the full power $V_z \cdot I$ where V_z is the Zener diode voltage, and I is the current through R_i, which is $(V_{in}-V_z)/R_i$. If the primary voltage source is a regulated supply, there is no need for further regulation, and the Zener diode can be used in series to drop the voltage. It will then dissipate only $V_z \cdot I_L$, where I_L is the actual load current being drawn.



Most IC regulators are either three terminal devices or three terminal devices with extra terminals for special functions. The three terminals are quite simply: input, output, and ground. The basic idea is to apply an input voltage which is above the dropout of the regulator, and below the maximum allowable input voltage. The output is then the rated output of the regulator. A simple model for the three terminal regulator is that of a series resistor which has a value determined by the output voltage. Note an important fact that is implied by this model: the regulator must dissipate the excess power that is not delivered by the load. On the other hand, there is no substantial standby current drawn, so for low current requirements, the regulator has very little power to dissipate. In this sense, the IC regulator is more like the series Zener regulator than the shunt regulator. For low currents, the input ripple is small, and the power dissipated by the regulator is essentially $(V_{in}-V_{out}) \cdot I_L$. However, we discussed earlier the fact that the actual input voltage in a proper design has a waveform something like the one shown at the right. This means that the average power dissipated is more like one-half of the larger value. In any case, except for currents that are on the order of 10% of the rated value, the IC regulator should have proper heat sinking. It will be found that most positive regulators are fairly easy to heat sink since the mounting surface is electrically common with ground. Thus, they can be mounted in contact with chassis ground.

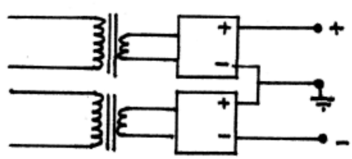




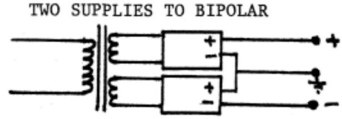
Regulators for negative voltages on the other hand generally do not have the mounting surface common to ground, and it is necessary to provide electrical insulation for the regulator, or to electrically insulate the heat sink. The IC regulators are often able to sense their own temperature and shut themselves down if they get too hot. In operation, it is possible to cautiously place a finger on the regulator to see if it is getting too hot. If you can hold your finger on it, it is probably okay.

IC regulators need some sort of compensation capacitors to keep them from having stability problems. In general, it is necessary to look at the literature on the regulator you are using to find out what type of capacitor is used, how big, and where it is placed. What seems to be most common is a capacitor on the input terminal to ground to be used if the regulator is mounted an "appreciable distance" from the capacitors in the unregulated supply. Since the term "appreciable distance" can refer to anything, you had probably better put them in to be safe. In the regulator circuits that we will be showing, these are generally put in. These are in parallel with the filter capacitors that follow the rectifier, and it is often confusing to beginners to see something like a 0.1 mfd capacitor in parallel with a 5000 mfd capacitor on a schematic diagram. The important thing is the physical placement of the smaller capacitor. These smaller capacitors are on the regulator terminals, and it is important that they are in fact mounted on the terminals and go to a solid ground with short leads. While these capacitors may not seem necessary when the power supply is first tested, they may be needed when it is put on the actual load. The same general thing can be said about capacitors on the output. These are often specified as not being necessary for stability but do improve the transient response. In general, these are a good idea. Some regulators have an upper limit specified for this capacitor; the idea being that the capacitor may draw too much current when first turned on and put the regulator right into current limit. However, many designs are used successfully with much larger capacitors, and in any case, there is often a fairly large accumulated capacitance on the output due to proper supply bypassing down the line. Many of the stabilizing capacitors are specified as being Tantalum electrolytics because they have a power factor more favorable for suppressing RF instabilities. Tantalum capacitors are expensive and somewhat hard to get. However, they should be used where they are specified so it is a good idea to get a few surplus capacitors to have on hand for power supplies. If you don't have the tantalum, try a normal electrolytic in parallel with a 0.1 mfd ceramic capacitor.

IC regulators come in three types: positive regulators, negative regulators, and tracking regulators (positive and negative). These types can be used with external pass transistors to increase their current output. A bipolar supply can be made in several ways. The simplest way conceptually is to make two identical supplies, ground the negative terminal of the first, and the positive terminal of the second. In this case, it is necessary that the two supplies have no electrical points in common until the output stage. This means that the two supplies either have to have their own transformers, or separate windings on the same transformer. A center tapped transformer will not work. The second method is to use the center tapped transformer to form a bipolar unregulated supply, and then to use a positive regulator for one polarity, and a negative regulator for the other side. Alternatively, the unregulated bipolar supply can be input into a tracking regulator.



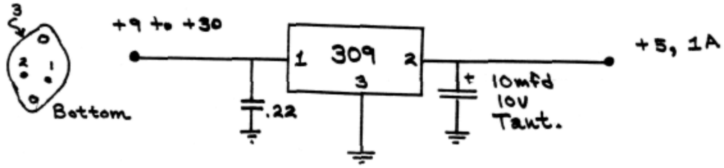
TWO SUPPLIES TO BIPOLAR

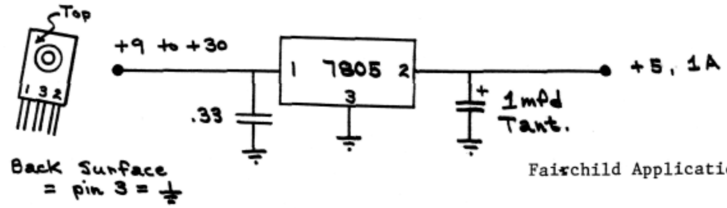


Utmost care should be used to connect regulators carefully. The pin connections can be confusing. If you test the unregulated supply first (as you should), be sure to discharge the filter capacitors before connecting the regulator to avoid costly errors.

INTEGRATED CIRCUIT REGULATOR CIRCUITS

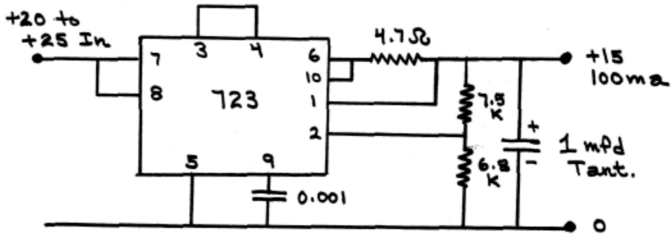
5 VOLT SUPPLIES: Five volt supplies are fairly simple to construct using either the LM309K regulator or the type 7805. The circuits are shown below. If only about 100 ma or less is needed, the LM309H can be used in place of the LM309K.



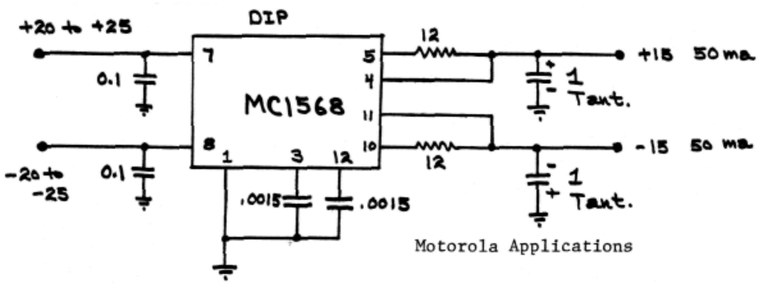


Fairchild Applications

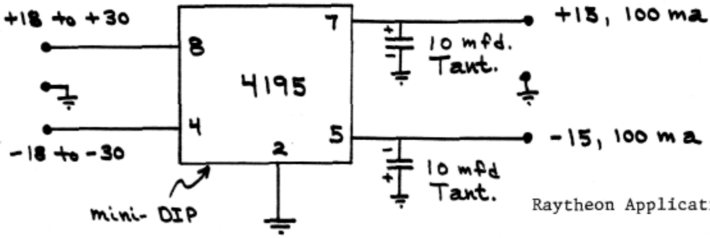
±15 VOLT, LOW CURRENT SUPPLIES: The type 723 regulator has been a favorite for some time. A basic +15 volt regulator is shown below good to 100 ma. Two of these can be used in the manner described on page 5j (6) to give a ±15 volt supply.



A tracking regulator can make a simple bipolar supply for low current requirements. Shown below are circuits using the MC1568 for a 50 ma supply and one using the Raytheon 4195 for a 100 ma supply.



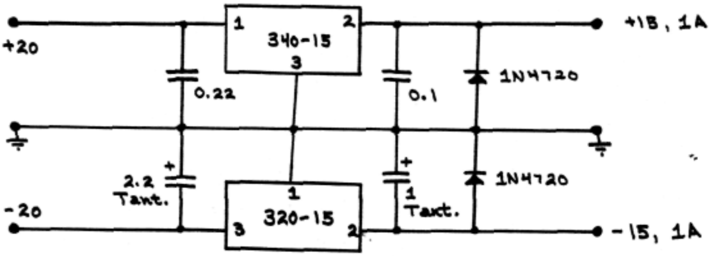
Motorola Applications

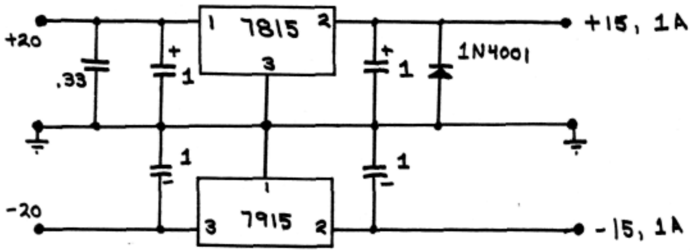


Raytheon Applications

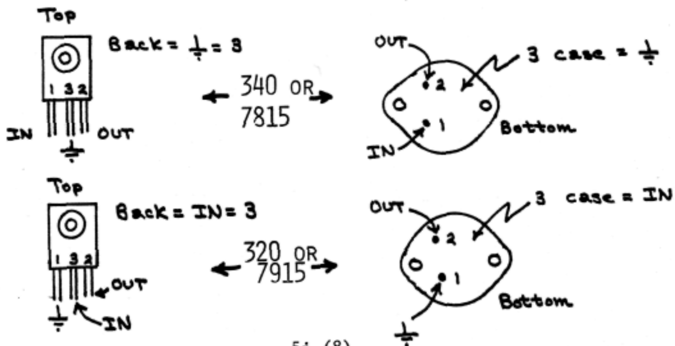
±15 VOLT, HIGH CURRENT REGULATORS:

When more current is needed, pass transistors can be added to the tracking regulators or three terminal positive and negative regulators can be used. The basic choices for the three terminal regulators are the type 340 and 320 combination, or the type 7815 and 7915 combination. The regulator circuits are shown below.

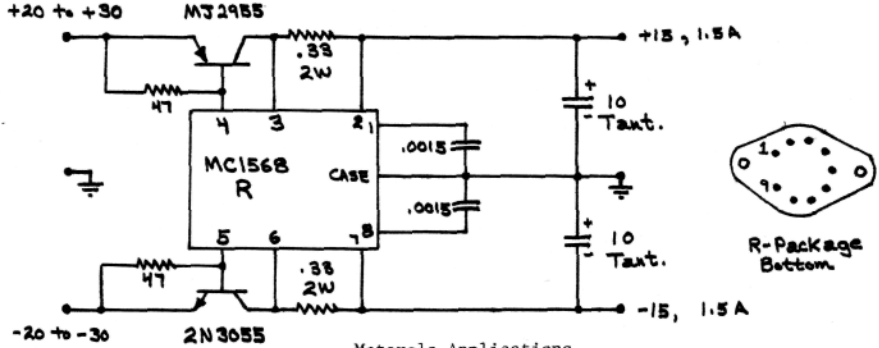




Motorola Applications



For higher currents, pass transistors can be added to the three terminal regulators, or to the tracking regulators. A circuit good to 1.5 amps is shown below. A similar circuit for a 2.5 amp supply can be found in the Raytheon applications notes on the type 4195 regulator.



Motorola Applications

PROTECTIVE CIRCUITS

Circuits using IC regulators are often protected fairly well by the regulators themselves. The following comments should prove useful to those who need additional protection.

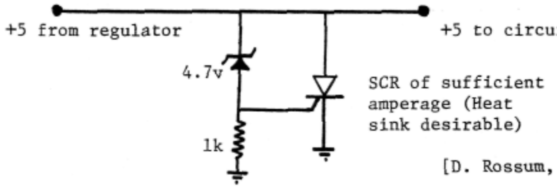
FUSE RATING: The overall supply should be fused at the AC power line. The value of the fuse is determined by power drawn, not current drawn from the supply. For example, a bipolar 15 volts supply at one amp delivers up to 30 watts, but the total power must also include the power dissipated in the regulator. If the V_{peak} value used is 22 volts for example, the power is 44 watts. Allowing for transformer and diode losses, probably about 60 watts is drawn from the AC line. This corresponds to about 1/2 amp, so the proper fuse value would be 3/4 amp or 1 amp of the slow-blow type.

CURRENT LIMITING: Current limiting is the maximum current that the regulator will pass before shutting down. This may be a built in feature of some regulators. Tracking regulators and some others have a current sense terminal. The output current is passed through a small value resistor (less than 1 ohm in many cases). When the voltage drop across this resistor approaches 0.6 volts (or lower if the chip is hot) a blocking transistor is activated to limit the current. The current sensing resistor is thus determined by something like $0.6/I_{max}$.

FOLDBACK CURRENT LIMITING: This is similar to current limiting, but here when the limit is reached (or if a short circuit reduces output voltage to zero), the current is cut back to less than the value it would deliver under a normal load.

THERMAL SHUTDOWN: Most of the newer regulators have the ability to sense their own temperature and shut down if they get too hot. The currents corresponding to this shutdown will depend on the heat sinking of the regulator.

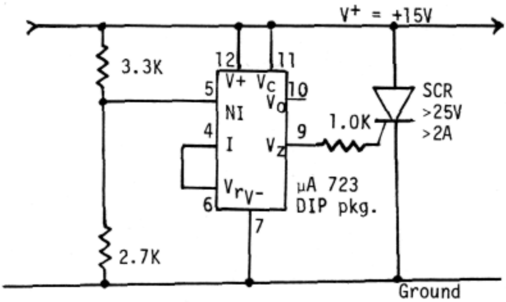
CROWBARS: The above features are mainly to protect the regulators, make them blowout proof, and indirectly to protect the attached circuit as well. A crowbar is a device added to the output to protect the attached circuitry from overvoltage. As soon as an overvoltage appears, the load current is shorted to ground by a SCR, holding the voltage to a very low value and either blowing the fuse or putting the regulator into a shutdown mode. Overvoltage could occur if the regulator failed and the unregulated voltage reached the output line. A far greater danger occurs when a 5 volt line is in the same circuit with a +15 volt line. With any amount of breadboarding at all, it is only a matter of time before the experimenter will short the two accidently and possibly destroy any TTL devices in the circuit. Thus, it certainly makes sense to add a crowbar to the 5 volt line. A suitable crowbar circuit is shown below and is recommended for any bench supply and for other supplies connected to expensive equipment. For a bench supply, it is very useful to have LED indicators to show when a supply is not putting out voltage as this may indicate that the crowbar has fired.



[D. Rossum, EN#35]

The crowbar circuit can be tested by touching +15 to +5 with no other circuitry attached to the supply. The SCR should fire and remain on even when the +15 is removed. To turn it off, turn the power off. It is also a good idea to see if the crowbar is triggered by any transients such as switches in the equipment or other power line switches nearby. If it is, it may be necessary to increase the Zener diode to 5.2 volts and/or add a bypass capacitor (start with 0.1 mfd) to the 5 volt line at the junction of this line and the Zener diode.

If the attached equipment is very valuable, it is perhaps a good idea to take the following steps in designing and installing a supply. (1) Use only factory first regulators, not surplus devices. (2) Stay well away from the maximum value for V_{peak} and draw less current than the rated amount. (3) On first installation, add diodes to the supply lines at the input of the equipment to prevent damage from accidental supply reversal. This is important if the supply is often attached and detached. In a final installation, the diodes can be removed. (4) A crowbar can be added to the 15 volt lines as well as the +5. A crowbar of this type is shown below:



To protect the -15 volt supply line, connect the +15 side of the circuit to ground, and the ground side to the -15 supply line.

[D. Rossum, EN#45]

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APPLICATION NOTE NO. 1

August 4, 1976

FIVE-VOLT ONE-AMP POWER SUPPLIES FOR TTL

The following notes give step-by-step instructions for making a one amp power supply based on the LM309K +5 volt three-terminal voltage regulator, or you can use the LM340 +5 regulator.

(1) The first step is the selection of a transformer. For this circuit, a transformer rated at a voltage from about 8 to 16 volts at one amp can be used. A standard 12.6 volt "filament" transformer can be used (Ignore the center tap wire if there is one - cut off and tape end, or connect to a blank terminal somewhere.). The higher the voltage of the transformer, the smaller the filter capacitor can be. Thus higher voltage transformers (up to 16 volts) are suggested where portable supplies are needed and lower voltages (8 volts) where stationary supplies are used since the larger filter capacitor can be tolerated in such cases, and less ripple and heat dissipation result in this setup. The AC line should be connected to the primary of the transformer and the proper output voltage verified (using for example, a simple multimeter).

(2) The next step is to convert the AC voltage from the secondary to DC. This forms an overvoltage, unregulated DC supply. (Note that the primary leads to a transformer are usually black while secondary leads are usually colored red, green, or yellow and a center tap is usually of mixed coloring). The full-wave "bridge" rectifier structure formed from four diodes is suggested. The diodes should be rated at one amp or higher, and at 100 volts or higher. (1N4002, 1N4003, 1N4004, 1N4005, 1N4820, etc., or a DIP bridge are good choices). See step two of the figure. After installing the bridge, the voltage output will read on a DC meter scale at a voltage in the neighborhood of the transformer secondary voltage.

(3) Next choose the filter capacitor. The formulas to do this can be found in Chapter 5J of the Musical Engineer's Handbook. For this application, just use the table below:

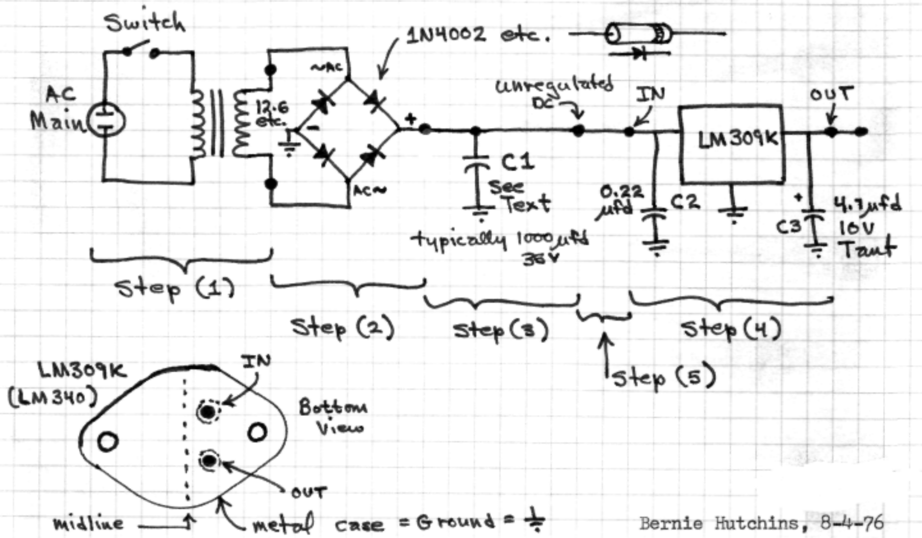
Transformer Voltage	Nominal Capacitor	Suggested Value = C1
8	2600 mfd	2200 to 4000 mfd 16v
10	1400 mfd	2000 mfd 25v
12.6	820 mfd	1000 mfd, 25v (35v OK)
14	720 mfd	1000 mfd, 25v (35v OK)
16	580 mfd	1000 mfd, 35v

The values above are somewhat conservative, and are for a full one amp output current. The capacitor value may be decreased in proportion to the actual output current. For example, if your circuit requires only 300 ma (0.3 amps), you can multiply the suggested values by 0.3. The power requirements for TTL can be obtained from TTL data books. For portable devices, the required current is often well determined. For lab type and experimenter supplies, the current varies with the device being tested, and it is probably best to use a capacitor so that the full one amp may be drawn. Connect up the capacitor making sure the polarity is correct (capacitor has either the + or - end marked). Turn on the power and measure the DC voltage. It should be about 1.4 times the transformer secondary voltage. This is because the capacitor holds the peak voltage of the AC cycle which is 1.414.... times the rated (RMS) value of the AC secondary. After verifying, turn the power off, and then short the capacitor. This will result in a moderate spark if you short it with a piece of wire, screwdriver, etc. You should discharge it now so that you don't surprise yourself when installing the regulator. The spark won't hurt you, but if you don't expect it, you may hurt yourself when you jump away. If you don't like sparks, short the capacitor with a 1000 ohm resistor, holding this in place about 10 seconds.

(4) Next install the regulator. This is the LM309K (or LM340 +5) which is a three terminal device. It has an input (from the unregulated DC supply you just made), an output (the +5 volts you want), and a ground. The regulator is particularly convenient since the ground "terminal" is the metal case. This means that you can mount the regulator in a metal chassis (which is usually ground) and the metal chassis will serve to give the necessary heat sinking to the regulator. Whether or not you need a heat sink depends on the amount of power being dissipated. The power is the product of the current being drawn out, and the voltage across the regulator. The voltage across the regulator is the unregulated DC input minus the +5 volt output. As a rule of thumb, if the current is 100 ma or less, no heat sink is required (the regulator case is enough). If the current is 500 ma or more, a heat sink should be used (that is, some extra heat sinking, metal chassis, metal plate, commercial power transistor type heat sink, etc.) If in doubt, calculate the power. If it's above 2 watts, use some heat sinking. In operation, the regulator should not be too hot to touch. We also suggest that the input and output capacitors C2 and C3 be used although they are not always necessary. Install these right on the regulator pins.

(5) Connect the unregulated DC to the input of the regulator and turn the supply on. The output of the regulator should be near +5 volts (from 4.8 to 5.2). The input to the regulator should be the same voltage it was before it was connected to the regulator (1.4 times the AC secondary). Next, connect up your load. The output voltage should remain at ~+5, or change by no more than a few tens of millivolts. The input voltage to the regulator will drop when the load is connected. The reading when read on ordinary meters should not drop below the midpoint voltage between the unregulated DC input (1.4 times the transformer secondary) and +7. For example, if you use a 12.6 volt transformer, the unregulated DC is about +17. Under full load, the unregulated input to the regulator should not read below +12. Also check the regulator for overheating after it has been on for 10 minutes or longer.

DIAGRAMS:



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APPLICATION NOTE NO. 2

August 11, 1976

BIPOLAR 15 VOLT SUPPLIES FOR OP-AMPS

The following notes give step-by-step instructions for making a bipolar supply, +15 and -15 volts, for op-amp circuits. The circuit is based on the LM340 and LM320 type regulators. There will be three leads coming out of the supply, +15, -15, and ground. The supply will deliver one amp current from each voltage. You could make a bipolar supply by connecting the + terminal of one supply to the - terminal of another, and call this connection point ground. This requires two supplies, and this means two transformers, or at least two separate secondary windings on the transformer. Here we will use the center tapped type of transformer, a bridge rectifier, and a positive or negative voltage regulator depending on which half the supply we are working on.

(1) The first step is the selection of a suitable transformer. The transformer should be rated at one amp and have a voltage from 28 to 48 volts, with the values between 30 and 40 being preferred. The transformer must have a center tap on the secondary for this application. Note that standard "filament" transformers are not suitable for this application since they come in only 12.6 and 24 volt sizes and these are outside the usable range, even when used in series combinations. In an emergency, three 12.6 volt transformers in series can be used for a 37.8 volt center tapped transformer with the center tap of the center transformer being the center tap of the combination. The AC line is connected to the primary of the transformer which is usually two black wires. The secondary wires are usually colored, and the center tap is usually of mixed coloring.

(2) The next step is to convert the AC voltage from the secondary to DC. This is done using a bridge rectifier formed from four diodes. The diodes should be rated at one amp or higher, and 100 volts or higher. (1N4002, 1N4003, 1N4004, 1N4005, 1N4820, etc. are good choices for diodes.) The diodes are arranged as in step two of the figure. Note that the center tap of the transformer is grounded. Check the setup using a DC scale on a multimeter. Connect the - terminal of the meter to ground, and the + to the + side of the bridge. The DC reading should be about half the secondary voltage. Repeat connecting the + terminal of the meter to ground, and the - terminal to the - side of the bridge.

(3) Next choose the filter capacitor. You will need two of these. For a full one amp supply, the capacitor should be matched to the voltage of the transformer secondary as follows:

Transformer Voltage	Nominal Capacitor	Suggested Value
15 volts (30 CT)	2080 mfd	2200 mfd 35v
17 volts (34 CT)	1225 mfd	1000 mfd 35v
18 volts (36 CT)	1016 mfd	1000 mfd 35v
20 volts (40 CT)	758 mfd	1000 mfd 35v
22 volts (44 CT)	604 mfd	1000 mfd 35v
Alternatives:		
14 volts (28 CT)*	3205 mfd	4000 mfd 25v
24 volts (48 CT)**	502 mfd	470 mfd 50v

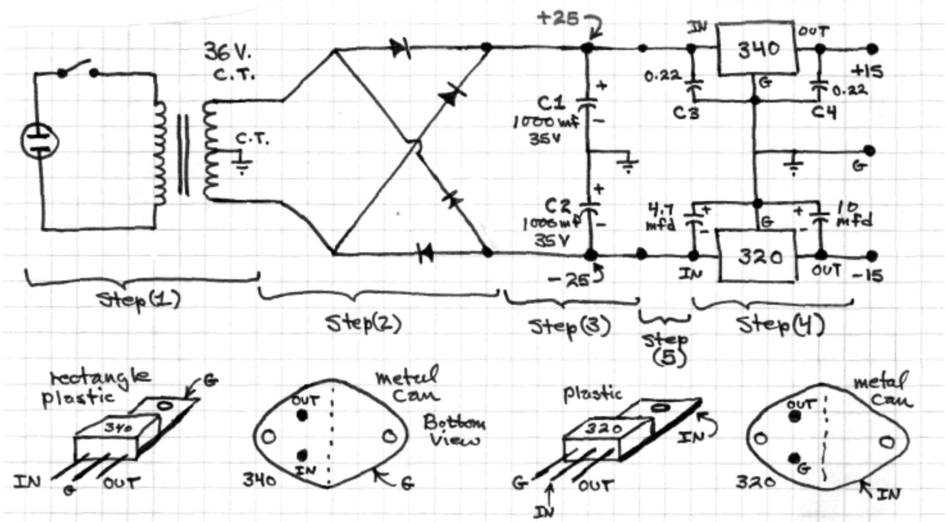
*suggested for fixed supplies - has lowest heat dissipation
**suggested only if first line, non-surplus, regulators are used.

These capacitors are installed as shown in step three of the diagram. Make sure the + and - terminals are connected correctly. Turn on the power and measure the voltages on the capacitors. The voltage should be 0.7 times the transformer secondary. (That's 1.4 times the center tapped voltage - right?). Typical values are shown on the diagram. After verifying the correct voltages, shut off the power and discharge both filter capacitors by shorting them with a screwdriver or piece of wire. If you don't like sparks, discharge them with a 1000 ohm resistor held in place for about 10 seconds.

(4) Next install the regulators. The LM340 is the +15 regulator and may come in the metal can with oblong base, or in the rectangular plastic package. This is easy to install in either case, as the large metal surface is the ground terminal. This makes it easy to heat sink. Some sort of heat sinking is necessary unless only about 100 ma or less is to be drawn. See AN-1, step 4 for more information on heat sinking. Install stabilizing capacitors C3 and C4 as shown. These should be mounted right on the regulator terminals. The LM320 is a little trickier to use since it is more difficult to heat sink, and because it requires larger stabilizing capacitors. The large metal surfaces of the LM320 are the input terminal, not ground. Thus, if heat sinking must be used, the heat sink must be insulated from ground. Alternatively, you can insulate the metal surface from the chassis with a mica washer and some insulated mounts. For currents from -15 of 100 ma or less, the LM320 rectangular plastic package is nice since it requires only one bolt to mount, or can be soldered in "standing up." Be sure to include the stabilizing capacitors on the LM320, and keep their leads as short as possible. Solder them right to the regulator pins.

(5) Connect the unregulated DC voltages to the inputs of the regulators. Turn on the power and measure the output voltages. Both the + 15 and the -15 should be within 0.6 volts of their nominal values. The voltages at the inputs to the regulators should be the same as they were when they were not attached to the regulators. Next connect up the load and the output voltages should not change very much (less than 3%). The input voltage may drop with the load connected, but should not drop below the midpoint of its original value and +17 volts. Check the regulator for overheating after it has been on a while. It is a good idea to load the LM320 with about 50% more than the expected current drain to see if it does anything funny. If there is no problem, you can go back to the original load with some assurance that things are working well. The LM340 will in general be less of a problem than the LM320.

DIAGRAMS:



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APPLICATION NOTE NO. 97
August 4, 1978

THE TRANSFERABLE POWER SUPPLY

"Transferable" from what to what? From "bench supply" to individual unit. This idea is one which we find particularly useful and one which also adds a measure of safety to your design and building operations. Basically, just about every electronic device you build needs a power supply. This is an inconvenience, an added expense, and involves dealing with the higher voltages of the AC lines. We can't offer much help on the expense, except to suggest careful shopping, especially for useful surplus lots of transformers. We do have some useful suggestions to make on convenience and safety however. First, let's look at different power supply requirements.

There are basically four types of power supply requirements as we see it:

1. The large bench supply. Typically this is capable of ±15 volts at one amp and possibly other voltages as needed. It is suitable for small and large projects, 100 IC's or more.
2. The small bench supply. Typically this is ±15 volts at 25 to 100 ma. It is suitable for basic experiments, as in an academic setup.
3. The large system supply. This is a large "in place" supply as you might have in a computer system or an electronic music synthesizer system.
4. The small system supply: This is the supply you need for a simple "stand alone" type of electronic device such as a sound processor or simple measuring instrument which must be moved around, but which can not be run on batteries. This is the real "nuisance" supply. The actual voltage or current requirements are similar to the small bench supply.

The point of this note is to take advantage of the similarity of the small bench supply and the small system supply so that one can be transferred to the other. There are numerous advantages to this arrangement:

1. You need make only one basic small supply. In an emergency, a bench supply can be put in service in the individual unit, and old unused individual units can have their supplies put back into services as bench supplies.
2. In the developmental stages of construction, you power the individual unit, which is inside its own box, from an external bench supply. Even though you will need to run the higher voltage AC lines inside the box of the individual unit later, for the developmental stage, the AC remains safely inside the bench supply unit. This prevents the builder, loose wires, or other devices from coming in contact with the dangerous AC lines (such as those running up to a panel off/on switch).
3. When construction is finished, the power supply unit is moved from the bench unit enclosure to a prearranged position inside the box of the individual unit, and the AC lines are connected up. Since this is the exact same supply used during construction, there should be no need to recalibrate any critical adjustments.

You should design your own transferable supply according to your own needs and resources. We will be giving one example later. For the moment, we will list the basic features of a transferable supply:

1. It contains a transformer, rectifier diodes, filter capacitors, and an IC regulator, all on the same PC board.
2. It has two input wires, the AC primary leads of the transformer (three if the AC ground return is used), and output terminals such as +15, -15, and ground. It may also have terminals for driving a pilot light.
3. It has a simple mounting that allows it to be mounted in a case for a bench supply and transferred easily to flat mounting in the individual unit.

EXAMPLE:

In this example, the PC board for the power supply was built on a 3½ x 6 base, the same size as the cover of a standard 3-3/4 x 6-1/4 x 2 bakelite cabinet. The outline for the PC layout is shown in Fig. 1. Everything here is mounted on the foil side of the board (see AN-15) and the only holes in the board are for mounting. The details of the IC regulator depend on the type used (see AN-98) and the exact spacing of the PC traces depends on the size of the transformer and filter capacitors. To complete the bench supply, an AC cord is run into the bakelite box, and a switch and output terminals are mounted in the box, well out of the way of components on the PC board when the power supply is mounted (see Fig. 2). In the actual instrument, a second AC cord is used, along with a second switch. The same mounting holes are then used when the PC board supply is transferred (see Fig. 3).

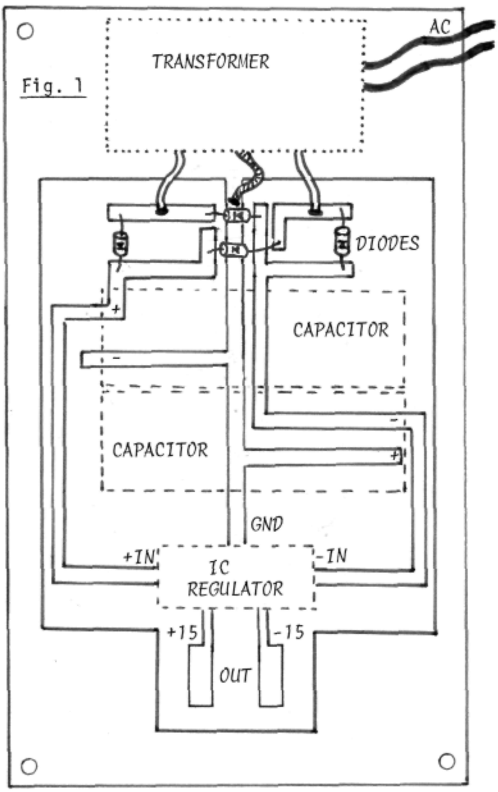
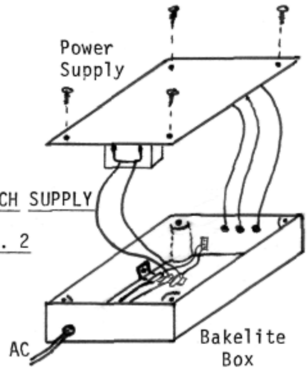


Fig. 1



BENCH SUPPLY

Fig. 2

EQUIPMENT MOUNTING

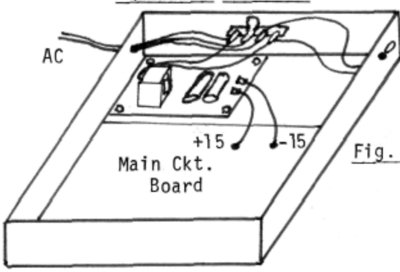


Fig. 3

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IC REGULATORS FOR SMALL BENCH SUPPLIES

In this note, we will be discussing some IC regulator circuits suitable for use in small bench supplies or in the "transferable" power supply discussed in AN-97. We will begin with a discussion of a more general problem in supply regulation - the problem of keeping the heat generated in the IC down to acceptable levels.

A typical regulator setup is shown in Fig. 1. The regulator is supplied by an input voltage from an unregulated supply. The unregulated supply consists of a transformer, diodes, and the filter capacitor C as shown. This unregulated voltage can be thought of as always coming from the capacitor, and this capacitor is charged each time the AC cycle goes to maximum value. Between extremes in the AC cycle, current flows from the capacitor and hence the voltage on the capacitor drops. There is thus considerable "ripple" on the input, as shown in Fig. 2. It is the job of the regulator to take this input and "slice" off the excess voltage, ripple and all. As should seem reasonable, this "slicing" action will cause some heating of the regulator. In fact, either Fig. 1 or Fig. 2 will show you that there is a voltage of $V_{in} - V_{out}$ across the regulator, and the current through the regulator is the output current I. Thus the power dissipated across the regulator is $(V_{in}-V_{out})I$. Note that while V_{out} is nearly a constant (the nominal output voltage of the regulator), the input voltage is variable due to the ripple, and thus we can use an average input voltage V_{ia} instead of the variable voltage, since we are interested in long term heating. It is interesting that as the current goes up, the average input voltage goes down. Thus, the power dissipated in the regulator does not go up exactly in proportion to the current, but at a slower rate.

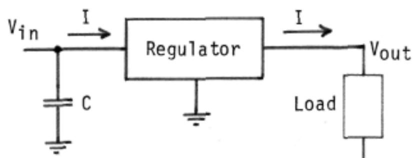

Fig. 1

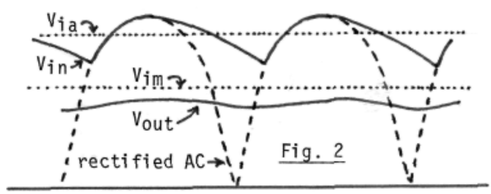

Fig. 2

There are really two things which we simply have to achieve with an IC regulator. First, the input voltage must not fall below a certain minimum (V_{im} in Fig. 2) which is typically about 3 volts above the nominal output, or else the regulator will drop out. Secondly, the IC regulator must not get too hot, or it will shut itself down. As a third, and often relatively unimportant condition, there is a very small ripple on the output (exaggerated in Fig. 2) which is smaller if the input ripple gets smaller. These factors lead to some interesting "trade-offs" in regulator design.

Probably an ideal supply would use a very large filter capacitor and a transformer with a secondary voltage such that the AC rectified peaks went only a few volts above V_{im}. This would mean that there would only be a few volts across the regulator (low power dissipation and heating) and yet the ripple would be small and well away from the minimum input voltage at all times. However, in practical cases, we often have to use smaller capacitors and transformers with higher output voltages (to allow for changes in actual AC line voltage for example). In this case, the following considerations become important. If C is made fairly small, the input ripple (and the output ripple - in consequence) increases. However, the "ripple rejection" of IC regulators is excellent, and this is of little concern. The only problem in using a small capacitor is that for larger current demands, the regulator may drop out on the discharge part of the cycle and glitch the supply line, and this is indeed a real problem if it does occur. Here however, we are looking at a small bench supply, and the current demands are low, and held to a maximum value by the dissipation of the regulator, not by the danger of the capacitor becoming discharged to the point where the regulator will drop out. Thus there are two things going for us in a small supply if we use a smaller capacitor. First, the capacitor will be physically smaller and take up less space. Secondly, the average input voltage will be lower and there will be less heating of the regulator.

Let's calculate how small the capacitor can be. We will use the approximate equation $C = I[\Delta t/\Delta v]$ for a capacitor discharge where I is the current, Δt is the time between charge cycles (1/120 sec. for a full-wave rectifier) and Δv is the full voltage between the peak of the AC cycle and the minimum input voltage v_{im}. For a small bench supply we might have I = 25 ma max, and the AC peak might be 27 volts while the minimum input voltage for a 15 volt regulator would be 17 volts, making Δv = 10 volts. Plugging in these values we get for C the surprisingly low value of 20 mfd., much lower than the 1000 mfd we often put in power supplies.

To test out these values, we constructed two identical supplies based around the LM325 dual tracking ±15 regulator. The circuit is shown in Fig. 3 below:

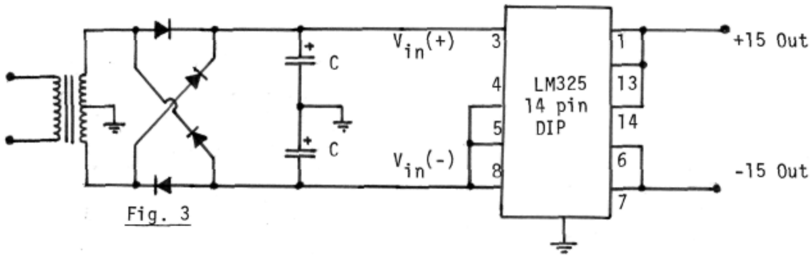

Fig. 3

In the unloaded state, the input voltages were about 29 volts for any value of C. By placing 620 ohm resistors on the outputs, the regulator was forced to supply 25 ma of current. We tried values of C of 1000 mfd, 22 mfd, 15 mfd, and 10 mfd. Small drop-outs were seen with the 10 mfd capacitor, but the others were large enough to hold 15 volts at the output at 25 ma. With C = 1000 mfd there was no measurable output ripple. With C = 15 mfd, the output ripple was 0.5 mv, corresponding to a ripple rejection (input to output) of about 74 db. This would not normally present a problem. With C = 1000 mfd, the average input voltage was 25.6 volts, giving a dissipation of 265 mw; with C = 15 mfd, the average input voltage was 22.8 volts, giving a dissipation of 195 mw, a 27% reduction. The "book value" for absolute max dissipation of the LM325 is 650 mw. In terms of actual heat, with C = 1000 mfd, the IC was too hot to touch, while with C = 15 mfd, the IC was hot but you could hold your finger on it indefinitely.

In other bench supplies we have successfully used the three-terminal type regulators in the TO-5 cans such as the 78M15 (+15) and the LM320-15. With the capacitor kept at a minimum value, these will supply from 50 to 75 ma. There is also no reason not to use the larger "power transistor" TO-3 packages, the standard for one amp supplies. These can be soldered in by the two pins, and a separate wire run to a bolt on one of the mounting holes. Without heat sink, you can get up to 200 ma out of these, keeping C to a minimum. [Note that the LM 325 pins given are for 14 pin DIP - many of the application notes give pinout for the TO-5 can. You can also use the type 1568 dual tracking regulator instead of the 325, but this requires some additional passive components.]