Section 8.0
Power Supply Design

8.0 POWER SUPPLY DESIGN

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8.1 SCOPE

The purpose of this section is to provide a practical guide for the selection of a power supply transformer and filter components. A number of basic assumptions are made to avoid an academic discussion of unnecessary material. For those interested in a rigorous theoretical analysis, there are a number of fine references available.

One of the more esoteric problems encountered by the circuit designer is the selection of power transformer ratings for a particular DC power supply. The designer is immediately confronted with a number of rectifier circuits and filter configurations. For the sake of simplicity, we will make some assumptions which should be valid for 99% of the average designer's applications.

FILTERS

We will immediately discard the consideration of choke input filters and confine our choice to capacitor input filters because of the following:

1. It is desirable to eliminate the weight and cost of chokes.
2. It can be assumed that the regulator circuit will provide sufficient extra ripple reduction so that an L-C section is not required. In addition, the regulator will compensate for the poor output voltage regulation with load, inherent in capacitor input systems.

The remaining disadvantages of the capacitive input filter system are caused by the discontinuous secondary current flow (high peak-to-average ratio of forward diode current). Current is drawn in short, high amplitude pulses to replace the charge of the filter capacitor which discharges into the load during diode off time. This results in higher effective RMS values of transformer secondary current. However, the transformer average VA rating is the same as the choke input filter because the higher DC output voltage obtained at the capacitor compensates for this effect. In addition, except perhaps for supplies handling very high currents, average semiconductor diodes will meet most of the peak or surge current requirements of capacitive filters.

RECTIFIER CIRCUIT

The remaining choice is that of a rectifier circuit configuration. The most common single phase circuits are:

1. Half-Wave (single diode)
2. Full-Wave Center-Tapped (two diodes)
3. Full-Wave Bridge (four diodes)
4. Dual Complementary Supply — "Full-Wave Center Tap" (four diodes)

The only advantages of the half-wave rectifier are its simplicity and the savings in cost of one diode. Its disadvantages are many:

1. Extremely high current spikes drawn during the capacitor charging interval (only one current surge per cycle). This current is limited only by the effective transformer and rectifier series impedance, but it must not be too high or it will result in rectifier damage. This short once-per-cycle current spike also results in very high secondary RMS currents.

2. The unidirectional DC current in the transformer secondary biases the transformer core with a component of DC flux density. As a result, more "iron" is needed to avoid core saturation.

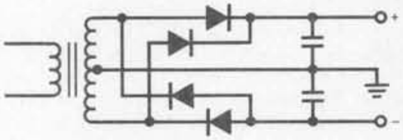
About the only time it would pay to consider using the half-wave rectifier is for very low DC power levels of about ½ watt or less. At these levels a power transformer cannot be reduced very much in size (at reasonable cost) and a small filter capacitor will be large enough for adequate DC smoothing.

The remaining single-phase rectifier circuits are of the "full-wave" type. Secondary current surges occur twice per cycle so that they are of smaller magnitude and the fundamental ripple frequency is double the supply frequency (i.e., 120 Hz rather than the 60 Hz of a half-wave system). All full-wave rectifiers also have the same basic rectified waveform applied to the filter capacitor.

OTHER FACTORS

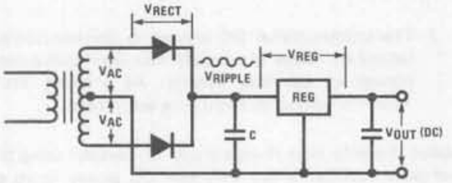
Full-Wave Center-Tap	**Full-Wave Bridge**
Uses ½ of secondary winding at a time	Uses full secondary winding continuously
Requires center-tap	No center-tap required
Uses 2 diodes	Uses 4 diodes

As can be seen above, the choice between FWCT and Bridge configurations is a tradeoff. The bridge rectifier has the best transformer utilization but requires the use of 4 diodes. The extra diodes result in twice the diode voltage drop of a FWCT circuit so that the latter may be preferable in low voltage supplies.



Dual Complementary Rectifier

The "dual complementary rectifier circuit" is the combination of two FWCT circuits and is a very efficient way of obtaining two identical outputs of reversed polarity sharing a common ground. It is also called a "center-tapped bridge rectifier."



Full Wave Center Tap

The above diagram represents a full-wave center-tapped rectifier using a capacitive filter and is the most common selection for moderate power, regulated DC supplies.

The following assumptions can be made:

1. V_{REG} must be 3 volts DC or greater.
2. V_{RECT} is about 1.25 volts DC.
3. V_{RIPPLE} is about 10% V_{DC} peak.

The following formula may be used for determining the transformer secondary voltage:

$$V_{AC} = \frac{(V_{OUT} + V_{REG} + V_{RECT} + V_{RIPPLE})}{0.92} \times \frac{V_{NOM}}{V_{LOW\ LINE}} \times \frac{1}{\sqrt{2}}$$

where: 0.92 = rectifier efficiency (typical)

$\frac{V_{NOM}}{V_{LOW\ LINE}}$ = the ratio of the nominal AC line voltage to the required low line conditions

A sample illustration of the above will be shown for a supply requiring an output of 5 V DC at 2 A DC to operate down to an input voltage of 95 V RMS.

$V_{OUT} = 5\ V$ $\quad V_{RECT} = 1.25\ V$

$V_{REG} = 3\ V$ $\quad V_{RIPPLE} = 0.5\ (1\ V\ p\text{-}p)$

$$V_{AC} = \frac{9.75}{0.92} \times \frac{115}{95} \times \frac{1}{\sqrt{2}} = 9.07\ V\ AC$$

Therefore, the transformer secondary voltage can be specified as about 18 V CT.

For a bridge rectifier of the same output requirements, the only change is that:

$$V_{RECT} = 2 \times 1.25 = 2.5\ V$$

As a result V_{AC} will be reformulated as:

$$V_{AC} = \frac{11}{0.92} \times \frac{115}{95} \times \frac{1}{\sqrt{2}} = 10.23\ V\ AC$$

So that the transformer secondary voltage now becomes about 10 V.

TRANSFORMER SECONDARY CURRENT

The remaining step is to determine the transformer RMS secondary circuit. This can be accurately determined only by complex analysis. However, for practical engineering purposes the chart below may be used.

Rectifier Type	Filter Type*	Required RMS Secondary Current Rating
Full-Wave Center-Tap	Choke Input	0.7 x DC Current
Full-Wave Center-Tap	Capacitor Input	1.2 x DC Current
Full-Wave Bridge	Choke Input	DC Current
Full-Wave Bridge	Capacitor Input	1.8 x DC Current

*Even though we have dropped choke input filters from this discussion, they are included for reference.

For instance, in our particular example (5 V, 2 A DC supply) the transformer RMS current would be:

for FWCT $1.2 \times 2 = 2.4\ A$

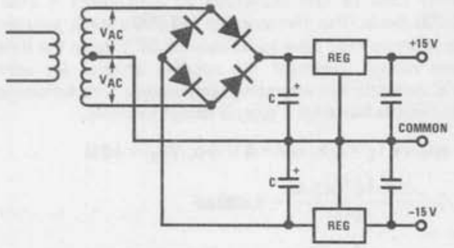
for bridge $1.8 \times 2 = 3.6\ A$

The total transformer specification would then be:

Circuit	Secondary Rating
FWCT	18 V CT @ 2.4 A RMS = 43.2 VA
bridge	10 V @ 3.6 A RMS = 36 VA

DUAL COMPLEMENTARY SUPPLY

One more common example will be given, i.e., a dual complementary supply for ±15 V @ 100 mA DC.



$V_{OUT} = \pm 15 \qquad V_{RECT} = 1.25$

$V_{REG} = 3 \qquad V_{RIPPLE} = 0.75\ (\approx 1.5\text{ V p-p})$

$$V_{AC} = \frac{(15 + 3 + 1.25 + 0.75)}{0.92} \times \frac{115}{95} \times \frac{1}{\sqrt{2}} = 18.6\text{ V}$$

$I_{AC} = 1.8 \times 100\text{ mA} = 180\text{ mA RMS}$

So that the transformer secondary rating is 37 V CT @ 180 mA RMS.

A precautionary calculation remains to be made. That is, the increase in voltage at the filter capacitor (into the regulator) caused by a high line condition. If we assume our highest line voltage to be 130 V AC then the transformer output (compared to low line) would rise by the ratio 130/95. In the 5 V supply, for instance, the following would happen:

$$V_{AC} = \frac{130}{95} \times 9 = 12.3\text{ V}$$

In the dual complementary ±15 V supply:

$$V_{AC} = \frac{130}{95} \times 18.6 = 25.5\text{ V}$$

The increase in output must be absorbed by the regulator, which results in higher regulator power dissipation. The illustrated values are safe for the typical IC regulator but should be checked in any specific application.

ADDITIONAL FACTORS TO BE CONSIDERED IN TRANSFORMER SELECTION

LOAD REGULATION

It has been assumed in the previous discussion of the change in transformer secondary voltage with line voltage that no change has been occurring in load current. Therefore, the transformers would seem to be ideal and the transformer secondary voltage (V_{AC}) will always be the same.

Actually, all the voltages calculated are assumed to be *full load*. Most reputable transformer manufacturers will rate their parts in this manner, i.e., secondary voltage at full load.

Since transformers are not ideal and have an internal impedance or "regulation" characteristic, variations in load current may cause a problem. If the load should be "light" at "high line," then there will be an additional rise in secondary voltage, beyond that due to the rising line voltage, caused by the decreasing voltage drop in the transformer windings.

Most smaller VA transformers (< 10 VA) have a load regulation of 20% or higher. This means that the transformer no-load voltage will be 20% or more higher than CTS rated full-load voltage. This must then be taken into account in the calculation of maximum V_{AC} (and DC voltage into regulator) with low load currents.

Due to the inherent design characteristics of transformers, "regulation" will vary inversely with size (or VA rating). In larger transformers size is determined primarily by the heat generated by internal losses. In smaller transformers (low VA rating) size is determined by the maximum permissible no-load to full-load regulation. Even though this is an important design limitation, virtually no transformer manufacturer publishes load regulation data in its catalog. Therefore, it would pay to check with the manufacturer in marginal applications.

TEMPERATURE RISE

In power transformers over 25 VA, temperature rise becomes a factor. The transformer may be constructed with materials capable of withstanding higher temperatures and be a perfectly valid design. However, the extra power dissipated may cause heating of nearby components.

This added power loss adds to the total power dissipated in the circuit area. The problem is not the internal temperature of the transformer but the actual increase in watts lost.

The actual power loss is also not normally published by transformer manufacturers, but may be obtained on request. It should be taken into account in the thermodynamic calculations of equipment temperature.

SHIELDING

Certain AC power line noise and transients will be fed through to the transformer secondary because of the capacitance between windings. This is a problem which is very difficult to analyze. Whether or not it is a problem in a particular application can best be determined empirically.

If such feedthrough is a problem the most common first step is to use an electrostatic shield between windings. This effectively reduces the inter-winding capacitance. An equal and sometimes superior approach is to choose transformers with non-concentric windings, i.e., with primary and secondary wound side-by-side rather than one over the other. Both result in at least order of magnitude reductions in capacitance. The "non-concentric" approach, however, also results in higher insulation resistance and makes it simpler to obtain higher insulation test voltages.

Certain types of feedthrough cannot be much affected by the transformer design and other approaches such as line filters or "MOVs" may have to be considered.

SUMMARY

This has been an attempt to provide a simple, practical method of determining transformer ratings. Certain basic assumptions have been made and this section is not meant as a rigorous academic analysis. However, such material is readily available in the literature (see footnotes). This, we feel, may help bridge the gap for the working designer.

Most transformer catalogs are quite mute regarding the extra details of transformer ratings. Therefore, some inquiries to the manufacturer and/or some empirical testing may be necessary to achieve an optimum selection. The electronic transformer industry is highly fractionalized and has no real industry standards. Therefore, it behooves the designer to be somewhat skeptical and to try to deal with reputable, established sources.

FOOTNOTES

1. Reuben Lee, *Electronic Transformers & Circuits*, 1947, John Wiley & Sons

   EE Staff – MIT, *Magnetic Circuits & Transformers*, 1943, John Wiley & Sons

   O. H. Schade, *Proc. IRE*, vol 31, p. 356, 1943

8.2 CAPACITOR SELECTION

For low current supplies ($I_{OUT} \leqslant 1\,A$) capacitor selection is relatively straightforward. Capacitance is found by the simple formula:

$$C = \frac{I_L}{\Delta V} \times 6 \times 10^{-3}$$

where: I_L = DC load current

ΔV = peak-to-peak ripple voltage

ripple frequency = 120 Hz

This yields 2000μF/amp for 3 V p-p ripple. At DC currents below 1 amp, capacitor heating is usually not a problem and peak-to-peak ripple voltage is the determining factor in capacitor size.

At higher values of capacitance, where the ratio of capacitor outside surface area to volume is significantly lower, internal heating becomes a problem. Ripple current rating may be the determining factor in capacitor selection, rather than ripple voltage. In many cases, capacitor size will have to be increased to prevent excessive internal heating. Manufacturers' data sheets should be consulted (after an initial selection is made) to ensure that capacitor ripple current ratings are met. Remember that the RMS ripple current ratings shown on capacitor data sheets are *not* the same as DC load current. RMS ripple current in a capacitor input filter is *2 to 3 times* the load current. In addition, the time-to-failure used to rate capacitors on data sheets is often 10,000 hours. For five-year life (40,000 hours), ambient temperature may have to be derated 30°C from the data sheet rating. Capacitor life roughly doubles for each 15°C reduction in operating temperature. The following calculations illustrate a typical design example:

assume $I_L = 3\,A$, $\Delta V = 4\,V$ p-p, $V_{DC} = 12\,V$

$$C = \frac{(6 \times 10^{-3})(3\,A)}{4\,V} = 4{,}500\,\mu F$$

Manufacturer's rating on a 4,600μF/20 V capacitor @ $T_A = 65°C$ is 3.1 A RMS. Dividing by 2.5 to convert from RMS ripple current to output current yields a maximum DC load current of 1.24 amps. Obviously either a larger capacitor is required or ambient temperature must be reduced.

As a final note, be sure to check whether the data sheet ratings are for still or moving air. Computer grade capacitors are often rated only for moving air. Other types may be rated for still air, and are therefore actually more conservatively rated.

Remember that capacitors are the number one cause of power supply failure. Don't let your supplies dominate the statistics column!

8.3 DIODE SELECTION

The RMS value of the current flowing into a capacitor input filter is 2 - 3 times the DC output current because the current is delivered in short pulses. Assuming a full-wave center tap or bridge, this means that although each diode is conducting only on alternate half cycles, it should be rated for *at least* the full output current. To ensure adequate surge capability during turn-on, a diode rating of at least twice the output current is recommended, especially for higher current supplies where the ratio of filter capacitance to output current is somewhat higher. Keep in mind that axial lead diodes achieve most of their heat sinking through the leads. Short leads soldered to large area standoffs or printed circuit pads are definitely recommended.

For "short circuit proof" IC regulated supplies using three-terminal regulators, an additional diode derating may have to be used. Long-term output shorts do not harm the regulator, which goes into a current limit or thermal limit mode to protect itself. The diodes, however, may experience a substantial current increase during the short. Regulator data sheets should be consulted for current limit values, keeping in mind that current limit is a function of input-output voltage differential. At high input voltages, the short circuit current of IC regulators is often less than full load current, tending to alleviate this problem.