Power Supply Design

August 1945 Radio-Craft

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Good power supply design has always been key to good system function. As with so many other topics in electronics, the basics of power supply design are the same now as they were in 1945 when this article appeared in *Radio-Craft* magazine. We now have transistors rather than vacuum tubes, but otherwise issues of voltage regulation, current supply, ripple, and power dissipation remain. Off-the-shelf power supplies have been and are available where engineers have designed generic or special purpose units with a set of specifications which a system designer uses to integrate them into their products. Many times, though, it is necessary or preferred to have the power supply on the same circuit board or in the same enclosure as the functional part of the product, so it is up to the designer to do it all. Even if you do use someone else's power supply design, you still need to understand the operation and limits. This rather involved article will help you regardless of your need.

Power Supply Design

By James E. Dolan

The complex problems of power supply design have in the past been considered too difficult for the average experimenter and constructor. Mr. Dolan has presented a simplified and very useful system of calculating constants of power supply filters.

The direct current and voltage delivered by the rectifier of a power supply includes an alternating current component. It is the duty of the filter section to remove this alternating current component to a degree governed by the use that the direct current is to be put to. This article will describe the commoner filter systems and tell how to calculate a filter system for a given requirement.

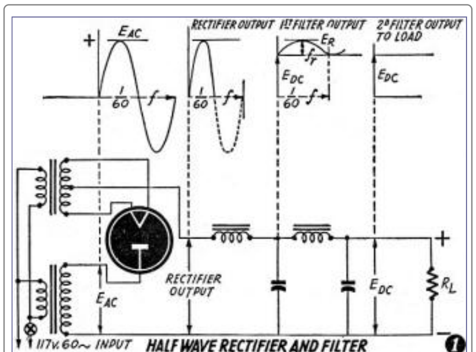

Fig. 1 - Half-wave rectifier and filter.

E_{ac} - Transformer secondary voltage. f - Frequency of supply voltage. f_r - Ripple frequency. E_{dc} - D.C. voltage, average. I_{dc} - D.C. current, average. R_1 - load resistance. E_r - peak value, fundamental component of ripple voltage. RF - ripple percentage. C - Capacity (farads).

The amount of filtering required for a specific purpose depends completely on the amount of alternating current hum permissible in the circuit. A microphone input channel will require excellent filtering because any hum present in this stage will be amplified in succeeding stages. Generally the alternating current component cannot exceed 0.005 of the direct current voltage for microphone input circuits. An audio-frequency amplifier may tolerate between 0.01 and 0.1 or more in the case of a class "B" stage. Some types of photoelectric equipment may tolerate 10% or even more. Certain switching circuits may be operated with no filter at all and still function reliably and accurately. In some cases a simple resistance-capacitor filter will be fully adequate.

Figs. 1 and 2 show a typical half-wave rectifier power supply system and a complete full-wave rectifier power supply. Above each diagram the functions and wave forms and proper nomenclature is indicated at each point along the filter system, the rectifier, and the transformer. By reference to these diagrams we can pick out the various components of voltage, current and frequency which arc tabulated beneath the diagrams. Because of the increasing impedance offered to harmonics by the filter and as the harmonic content of the wave fed into the filter is small, if the filter is designed to handle the fundamental component of the ripple frequency it will suppress all harmonics, so the ripple due to harmonics need not be considered.

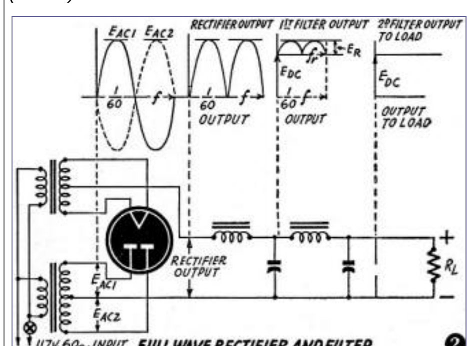

Fig. 2 - Full-wave rectifier and filter.

The ripple frequency is a function of the supply voltage and the type of rectification used. A half-wave rectifier delivers a ripple frequency equal to the supply frequency. A full-wave or a bridge system of rectification delivers a ripple frequency to the filter equal to twice the supply frequency.

The condenser input filter is of particular value in low-current circuits because of the fact that for a low current drain the filter condenser can supply the required voltage to the load during its discharging cycle. By the same token, the voltage output of the condenser into a low-current load approaches the peak value of the impressed voltage delivered by the rectifier tube or tubes.

This type of set-up is economical as far as trans former and rectifier costs go, but requires twice the filtering of a full-wave rectifier system if the same ripple voltage is to be attained in both cases. The effectiveness of the voltage-gaining properties of the condenser input filter decrease with an increase in the current drawn by the load. This means

poor regulation. With a half-wave rectifier the effect on the transformer is such as to reduce its efficiency by saturating the core and secondary winding with direct current, making for less efficient transformer operation. On the other hand, if the current drain is small and a high voltage is needed, this type of filter and rectifier system may be most economical and desirable. If a supply is desired for the high voltage on a cathode ray oscillograph, this type of circuit will answer the purpose in an excellent manner; the cost of parts is low, the circuit is compact, and of most importance, the current drain is low and stable. Under these conditions half-wave rectification and condenser input are not only possible but advisable.

Three types of rectifier systems are commonly in use for single-phase current rectification, the half-wave, the full-wave, and the bridge rectifier. We may construct a chart to show the characteristics of the various types of rectifier systems and include the data required for filter circuit design. Such a chart is given in Table 1.

	Half Wave	Full Wave	Bridge
E_{dc} Direct current component	1.0	1.0	1.0
E_{ac} RMS transformer Voltage	varies	1.11	1.11
f_r Fundamental ripple frequency	60	120	120
E_r Peak value of alternating current component of rectifier output	variable factor	.667	.667

Table I - Characteristics of the various types of rectifier systems and include the data required for filter circuit design.

The first and most important consideration is the amount of alternating current component at the input of the filter. This is given in the above table and is a consequence of the type of rectifier used. In the case of the half-wave system it is also a consequence of the amount of current drawn and the type of filter used. For the full-wave rectifier the value of the alternating component is 0.667 of the direct current component; and for the bridge rectifier circuit it is also 0.667 of the direct current component of the rectified output wave form.

There are three types of filter circuit to be considered in this discussion, the first being a filter consisting of only a choke and condenser; the second consisting of a two-section filter, two chokes and two condensers; the third, the resistance filter.

In considering the first filter input condenser, there are two important considerations; the smoothing effect, and the effect of the condenser on the available voltage. The actual formulae and engineering calculations involved in the calculation of the true effects of the input condenser are complicated and involve consideration of the voltage source impedance, the resistance of the rectifier tube, the input capacity, and the leakage reactance in an involved relationship. A few simple graphs will illustrate the effects of this input condenser in a manner which will be fully satisfactory for all practical uses.

Fig. 3 is a graph illustrating the variation of voltage for various load currents and different values of capacity utilized as input condensers. We note that increasing current will lower the voltage, thus causing poor regulation. The wide space occupied by the curves further indicate the poor regulation as also does the percentage voltage change for varying loads. The use of this chart is self-explanatory and no difficulty is likely to be experienced by anyone who understands radio fundamentals.

The graph in Fig. 4 indicates the ripple percentage resulting from various values of capacity and load resistance. We note here that in all of these calculations the effect of both capacity and load resistance and load current are very important in their effects on ripple.

The graphs in figures 3 and 4 are both for 120-cyc1e ripple frequency as would be the case for full-wave or bridge rectifiers. The use of condenser input for half-wave systems is not recommended except under the conditions previously noted. One effect of condenser input is to produce a higher peak voltage and current on the rectifier tube or tubes than is imposed with the choke input system. The ratio of peak to average plate tube current is higher.

The most important considerations involved in the calculation of filter output voltage using condenser input are the source impedance, which consists of the leakage reactance and resistance of the transformer, the tube resistance, and the resistance of the load; the value of the condenser not being of prime importance. The important considerations in reference to filtering ability and the reduction of ripple voltage are the actual capacity and the load resistance. Later on in this discussion an example of the calculation of a condenser input filter shall be given and the means of using these charts and graphs will be readily apparent.

We may now proceed to the choke input filter consisting of a choke followed by a condenser as shown in Fig. 5. The formula for the determination of the amount of ripple voltage that this type of filter will pass with various values of L and C is:

$$E_r \text{ across load} = \frac{E_r \text{ at input}}{(2\pi f)^2\, LC} \quad (1)$$

As the ripple factor is what we are interested in we will work out the equation for this factor. Let us assume a full wave or bridge rectifier, then E_r at the input to the filter will be 0.667 E_{dc} and f_r will be 120 cycles. Substituting these values in this equation (1) we find our next equation to be:

$$E_r \text{ across load} = \frac{.667\ Edc}{(6.28 \times 120)^2 \times LC} = \frac{.667\ Edc}{568500\ LC}$$

$$= \frac{.0000012\ Edc}{LC} = 10^{-7}\,\frac{12\ Edc}{LC}$$

But, as the factor we desire is the ripple factor which is equal to E_r divided by E_{dc}, we must divide this equation by E_{dc} to find the ripple factor. Doing this we have:

$$\text{Ripple factor} = \frac{\text{Er across load}}{Edc} = 10^{-7} \times \frac{12\ Edc}{LC} \times \frac{1}{Edc}$$

$$= 10^{-7} \times \frac{12}{LC} \quad (2)$$

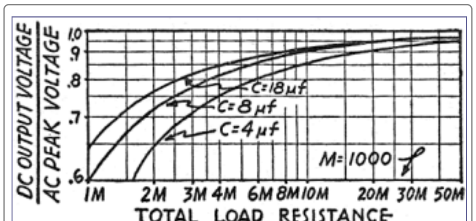

Fig. 3 - D.C. output vs. A.C. peak voltages.

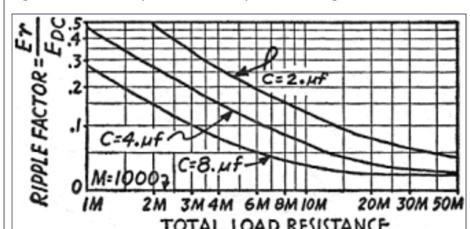

Fig. 4 - Ripple at filter input and output.

In use this formula should be used for full-wave or bridge rectification only as the ripple frequency has been assumed to be 120 cycles and the peak value of the alternating current component of the rectified direct current is taken as being 0.667 of the direct current voltage. For half-wave calculating the ripple frequency will be 60 cycles and the above equations can be worked out with that value merely by substitution of 60 in place of 120 in the formula. Value of the peak alternating current component will vary with the load drawn but a figure of 0.7 can be used in calculations. For heavy loads and to allow a margin of safety it would be better to use a higher figure. About 0.8 should be fully satisfactory. It is difficult to give an exact figure, but for all practical uses and purposes, those given above will prove fully satisfactory.

In all our choke-input filter designs it is supposed that the input inductance is of sufficient size as to maintain a continuous flow of current through the circuit under operating conditions. This is a function of the actual inductance, the .resistance of the load, the alternating current component of the rectified wave, and the direct current voltage output of the rectifier system. As the last two mentioned figures represent a constant for any given type of rectification, a simple formula will show the minimum amount of inductance required to satisfy the conditions of maintaining current flow throughout the entire 360 electrical degrees:

For 60 cycle ripple:

$$L = \frac{R_L}{565} \qquad (3)$$

For 120 cycle ripple:

$$L = \frac{R_L}{1130} \qquad (4)$$

Unless these minimum amounts of inductance are used the formulas and graphs given for choke input filter design cannot be used with accuracy. Imperfect filtering and high peak tube currents will result from a deficiency of inductance, with possible damage to the rectifier tubes. In the case of a varying load on the rectifier and filter system the conditions of minimum inductance must be observed at all times. To accomplish this it may be desirable to connect a bleeder across the output of the filter in order to maintain a minimum amount of current flow. Another method often used is to use a "swinging choke" in the input of the filter. A swinging choke has a relatively high inductance for low current, which drops with increasing current. By reference to the proper formula, which will depend on the type of rectification, and by use of the maximum and minimum inductance values, it is easy to select the proper choke so that flow will be maintained for all values of current.

Our next consideration is the two-section filter shown in Fig. 1 or 2. In this case, we have merely used two single sections, one following the other. The amount of ripple voltage present at the output of this type of filter is calculated from the following formula:

$$E_r \text{ across load} = 10^{-14} \frac{206\ Edc}{L_1 C_1 L_2 C_2} \quad (5)$$

and to find the ripple factor we have:

$$\text{Ripple Factor} = 10^{-14} \frac{206}{L_1 C_1 L_2 C_2} \quad (6)$$

In working with this formula it is best to have the product of the first section of the filter approximately equal to the LC product ofthc second section. The above formulas, numbers (5) and (6) are for use with 120-cycle ripple frequencies. For 60-cycle ripple frequencies (as would be encountered with half wave rectification) the numerator of both fractions would be changed from 206 to 34 and the fractional multiplier changed from 10^{-14} to 10^{-12}.

Another method of effective filtering commonly used for low-current applications is that in which resistors replace the chokes in the standard type of filter. This type of filtering is advantageous because resistors are lower in cost than inductances, thereby lowering the cost. The amount of filtering is a function of the load resistance and the values of the filter components. An approximation is given for the amount of filtering by the following formula:

$$\text{Ripple factor} = 10^{-5} \frac{177}{RC} \quad (9)$$

This formula is for 60-cycle ripple frequency:

$$\text{Ripple factor} = 10^{-5} \frac{88}{RC} \quad (10)$$

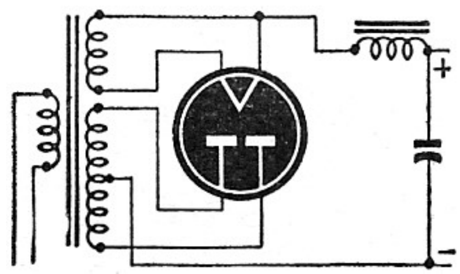

Fig. 5 - Power supply with choke-input filter.

This second formula (8) is for 120-cycle ripple frequency as would be present in full wave and bridge rectifiers. It must be remembered that the resistance introduced into the circuit by the use of a resistor-capacitor filter will lower the available voltage at the filter output. The voltage drop will increase with increasing current. The above formulas are for a single-section filter consisting of one resistor followed by one condenser.

Let us solve two problems: the first dealing with a single section choke input filter; the second, a two-section filter with condenser input.

In our first problem we desire to secure a certain voltage to the load and to find out what degree of filtering will result under the following conditions:

Given: Direct voltage to the load: 340 volts.

Rectification: Full wave, type 80 tube.

Current :125 milliamperes, load current.

Choke: 30 henrys, 160 ohms resistance.

Condenser: 4.0 Microfarads. Power input: 60-cycle.

We wish to find:

The transformer voltage each side of center tap.

The ripple factor to the load.

The actual amount of alternating current voltage at the load.

Our first consideration is the voltage drop in the choke. As the current is 0.125 amperes and the resistance is 160 ohms, the voltage drop through the choke is 20. The rectifier must therefore supply 360 volts to the filter input. By consulting a tube manual we find the voltage drop, at 125 milliamperes, through the type 80 tube to be 62 volts. The transformer must then supply 360 plus 62 volts or 412 volts. Multiplying this figure by the full-wave rectification factor 1.11 we find that the transformer must deliver 457 volts. A commercial transformer would deliver 450 volts. By using a choke of lower resistance, about 100 ohms, the voltage drop through the choke will be reduced with a subsequent raising of the voltage to the load.

Using formula (3) we find the ripple factor:

$$\text{R.F.} = \frac{12}{30 \times 4 \times 10^{-6}} \times 10^{-7}$$

The foregoing expression is equivalent to :

$12/120 \times 10^{-1}$

And the ripple factor (R.F.) equals 0.01.

As this is equal to E_r/E_{dc} and the direct current voltage is 340 volts then the actual ripple voltage, E_r is equal to 340 x 0.01 or 3.4 volts. It should be remembered that "C" is in farads in all of these formulas. To convert to microfarads from farads the microfarads must be multiplied by 10^{-6}.

The second problem involves a two-section condenser-input filter. We wish to find the ripple voltage and the ripple factor under the given conditions.

Given: Direct current to load: 400 volts.

Current: 200 milliamperes.

Full wave rectification.

Power input: 60 cycle.

Input condenser: 8.0 microfarads.

There are two filter condensers, each 4.0 microfarads.

There are two chokes, each 12 henrys, 80 ohms resistance.

To find: Transformer voltage each side of center tap.

Ripple voltage.

Ripple factor.

The problem must work from the load to the power input. The resistance of the chokes is 160 ohms and the current is 0.2 ampere, therefore the voltage drop through the filter is 32 volts and the voltage input to the first choke of the filter from the condenser must be 4.32 volts. The input condenser is working into an actual load of 2000 ohms load resistance plus the resistance of the chokes, 160 ohms, or a total of 2160 ohms, total load resistance presented at the input of the first choke of the filter. We now make use of the graphs of figures 3 and 4 for our condenser calculations. Figure 3 is the graph of load resistance, E_{dc} and transformer peak voltage. This graph takes into account the resistance and impedance of the transformer and the rectifier tube or tubes and it is not necessary to add tube voltage drops, as the graph incorporates this figure. The transformer voltage is given in terms of peak voltage. Multiply by 0.707 to find the R.M.S. voltage. We know our load resistance is 2160 ohms; finding the point representing this resistance and going up to the proper capacity curve, then referring to the left-hand column we find that the D.C. at the input condenser terminals under the given conditions is 0.73 of the peak AC. voltage, or:

432 equals 0.73 x A.C. peak voltage and A.C. peak voltage = 592 volts.

Converting to R.M.S. values:

AC. R.M.S. voltage = 0.707 A.C. peak and 0.707 x 592 = 419 volts.

The required A.C. R.M.S. voltage each side of the transformer center tap will be 419 volts.

To find the ripple voltage we consult the graph of Fig. 4 .and, finding the load resistance on the base line, go up to the proper capacity curve and read off to the left side of the graph the ripple factor. In this case it is 0.13, which means the actual E_r at the condenser terminals is 0.13 x 432 or 56.2 volts. The formula for the calculation of the ripple factor of a two-section choke input given at (7) is:

$$\text{R.F.} = 10^{-14} \times \frac{206}{L_1 C_1 L_2 C_2}$$

and substituting the given values:

$$\text{R.F.} = 10^{-14} \times \frac{206}{12 \text{x} 4 \text{x} 10^{-6} \text{x} 12 \text{x} 4 \text{x} 10^{-6}}$$

$$= 10^{-2} \times \frac{206}{2304} = 10^{-2} \times .089$$

And R.F. = 0.00089 or 0.0009

The actual ripple voltage to the load is'

E_r = 0.0009 x 400 or 0.36 volt

Thus we have found the required transformer voltage, the ripple factor, and the actual ripple voltage.

These calculations are approximate due to the many variable factors involved, such as the reactance and impedance of the voltage source, resistance of the tube used, phase characteristics of the load, the resistance of the load and the amount of current, as well as other factors involved.

Resistance-capacitance filters follow a similar line as the single section choke filter. By study of our first problem and working along like lines but using the proper formula, either (8) or (9), any resistance-capacitance filter calculation can be made.

Posted February 2, 2021