

RECTIFIER, TRANSFORMER AND FILTER DESIGN

BY

G. P. MCCOUCH & P. K. MCELROY

I. INTRODUCTION.

Most power supplies for use in electronic instruments transform the incoming line voltage to a suitable value, rectify it, and filter the resultant dc in a straightforward and thoroughly calculable manner. Calculations should be performed not merely to minimize trial and error in securing the desired output but primarily to ensure an economical and reliable design in which each element operates within its ratings. This design procedure, used in conjunction with ESPD-TR, IRON-CORED COIL WINDINGS, and applicable specifications on capacitors and rectifiers, permits rigorous design of dc power supplies.¹ It replaces, for all but the roughest purposes, the paragraph in ESPD-TR titled CURRENT DENSITY.

The transformer must be designed with sufficient copper to keep the temperature rise acceptable; to do so requires a knowledge of the effective (rms) current. This current depends not only on the load current but also on the choice of rectifier and filter circuits and, in particular, on the value of current-limiting resistance in the circuit (R_f in Figure 1).

In order to choose a rectifier with suitable ratings, the surge and peak currents as well as the effective current must be known. The rectifier must be protected from too great a

current inrush (surge current) when the power is first supplied to the rectifier, that is, with a completely discharged first filter capacitor. This problem never arose with a vacuum tube with a heated cathode; even the time to bring a direct-heated filament up to temperature would control the inrush. Selenium and silicon rectifiers, on the other hand, are instantaneously in full operating condition, and hence are current limited only by the source impedance, unless added resistance (R_f , see Figure 1) is employed. Tuttle, who has studied these rectifiers exhaustively, says that if the effective or rms current through the rectifier is limited to 2.5 times the rated dc for the rectifier in a half-wave circuit, the current inrush will be limited to a value the rectifiers can tolerate. Most modern semiconductor rectifiers carry explicit surge ratings.

In order to obtain satisfactory capacitor life, it is not only necessary to operate within the dc voltage ratings but also within the ripple current rating. The capacitor ripple current must be limited for two reasons:

- a. The capacitor may overheat and slowly deteriorate by drying out, or even explode.
- b. The inverse voltage drop caused by the ripple current gradually forms up the cathode, reducing its capacitance from infinite to a finite value, thus reducing with time, in many cases, the terminal capacitance of the capacitor.

¹ An excellent supplementary reference is:

O. H. Schade, "Analysis of Rectifier Operation," Proc. IRE, Vol 31, pp 341-361, July 1943.

We shall first show a generalized circuit in order to define terms used subsequently, then make some general observations concerning choke input and large capacitor input filters, and comments on the choice of circuit. Design curves and formulas will then be presented, which permit determination of voltages, currents, circuit resistance, transformer utilization, and illustrate various interrelationships between these quantities. Fortunately, the only calculations required are simple arithmetic, and most of the required information can be obtained directly from the design curves.

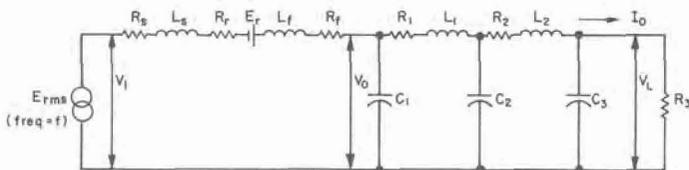


Figure 1. Generalized rectifier-filter circuit.

II. GENERALIZED CIRCUIT.

This sketch, Figure 1, is a generalized one. It is not necessary that all components shown here should appear in every case. Those not appearing in the user's circuit will, of course, be omitted.

Here are observations about the various quantities shown:

- E_{rms} - This is the rms open-circuit value of voltage supplying the rectifier-filter system, which should be the transformer input voltage times the turns ratio. It equals $\frac{V_1}{\sqrt{2}}$.
- V_1 - This is the peak open-circuit value of voltage supplying the rectifier-filter system. It equals $\sqrt{2} \times E_{rms}$.
- R_s - This is the resistance of the source. It consists of the reflected value of the hot dc resistance of the primary, plus that (if any) of the power source, plus the hot dc resistance of the rectifier secondary (the average of the two halves if this is full-wave). (Although this is now usually referred as a "center-tapped full-wave" rectifier, the older simpler "full-wave" term is retained for consistency with the Transformer Manual.) At 40°C rise, resistance is increased about 15% over room-temperature value.
- R_r - This is the forward resistance of the rectifier. In the case of a hard electron tube, this value is not constant, but no serious error will be introduced if it is assumed to be constant, deriving it from the published values of voltage drop at given current.
- E_r - This is the voltage drop in the case of a rectifier where this rather than the resistance is a constant.

Mercury and other gaseous rectifier tubes fulfill this condition, and the drop in a silicon rectifier may need to be taken into account in low-voltage designs.

- $R_r + E_r$ - In some cases, it may be helpful to use both of these to simulate the rectifier. This is useful, for instance, in the case of a selenium rectifier where the voltage-versus-current curve first jumps suddenly and then starts off along a sloping straight line. E_r would be the intercept of the sloping line on the voltage axis, R_r its slope.
- L_s - This is the inductance of the source, otherwise leakage inductance. It will usually be ignored, except in the case of sophisticated calculations or in very heavily loaded cases where the drop across the load is much less than that through the several parts of the source.
- L_f - This is the feed inductor. Its reactance in henrys should be equal to at least $\frac{1}{1000}$ of the load resistance in ohms or $\frac{R_1 + R_2 + R_3}{1000}$ in the case of full-wave rectification from a 60-cycle supply. For other supply frequencies, multiply inductance by 60/f.
- R_f - This is the feed resistor. If there is a feed inductor, it is the resistance thereof. Otherwise, if it exists, it is the resistor added in to keep the effective current through the rectifier within bounds.
- V_0 - This is the dc voltage across the input filter capacitor.
- C_1 - Input capacitor.
- C_2
 C_3 } - Other filter capacitors if employed.
- L_1
 L_2 } - Filter inductors if employed.
- R_1
 R_2 } - If there are filter inductors, these resistors are usually the resistances of the inductors. If there are no inductors, they are the filtering resistors, if present.
- V_L - This is the dc load voltage.
- R_3 - This is the equivalent resistance of the dc load, which equals $\frac{V_L}{I_0}$.

III. FILTERS.

A. Choke-Fed Filters.

These are generally used only with full-wave rectifiers. With half-wave rectifiers, the size of the inductor needed to store enough energy for the long off period gets preposterous. In the full-wave case:

$$I_{rms} = 0.75 I_o$$

(Hard Tubes)

$$E_{rms} = 1.11 I_o (R_s + R_r + R_f + R_1 + R_2 + R_3)$$

(Gas tubes)

$$E_{rms} = 1.11 [e_r + I_o (R_s + R_f + R_1 + R_2 + R_3)]$$

(Semiconductors)

$$E_{rms} = 1.11 [e_r + I_o (R_s + R_r + R_f + R_1 + R_2 + R_3)]$$

All values on the right side of these equations have been established once the rectifier is chosen and the design of the filter established, except the value of R_s , which is somewhat uncertain. The primary contribution can be calculated fairly closely from an intelligent rough guess at the value of E_{rms} , enabling one to calculate the reflected value. The guess for E_{rms} will also give a rough first idea of the rectifier secondary turns. From this a secondary contribution to R_s may be calculated using a wire size appropriate for $\frac{3}{4}$ of I_o (for the full-wave case). If the E_{rms} thus calculated is too far from the guess on which R_s was based, generally only one more guess is required to get sufficient agreement.

B. Large (Quasi-Infinite)-Capacitor-Fed Filter.

The beautiful simplicity of the choke-fed case does not carry over to instances where the first filter element is a very large capacitor, or even a small capacitor. Whereas the rectifier is conducting constantly in the choke-fed case, the conduction angle of the capacitor-fed case is always less than 180° . It repeats once a cycle for half wave and twice a cycle for full wave. Figure 2 shows roughly how this looks in the full-wave case, both voltage across C_1 and the successive current waves through a full-wave rectifier being shown. It will be fairly obvious how to modify the picture if half-wave rectification is employed.

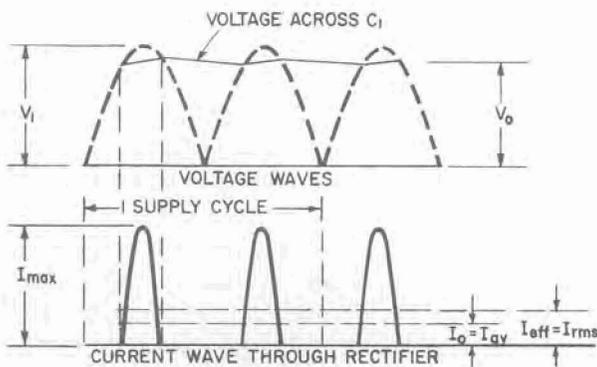


Figure 2. Capacitor-input filter waveforms.

The use of electrolytic capacitors at filter inputs has reduced input ripple voltage to the point where the capacitance can be considered infinite for purposes of calculation of the currents in the transformers and rectifiers. It can be seen that the voltage across C_1 would be a flat horizontal line if C_1 were infinite. Under such conditions there would be no hum or ripple on the rectified dc, and the conduction angle would be symmetrically disposed about the 90° voltage maximum.

Perhaps the easiest way to understand what goes on here is to consider what happens in the circuit as the ratio between source and load resistances varies. In Figure 1, C_1 separates source and load with respect to itself, respectively at left and right. C_1 belongs to neither alone, yet contributes to the character of each.

For these purposes, let:

$R = R_s + R_r + R_f$ and $R_o = R_1 + R_2 + R_3$. The ratio R/R_o then determines the conduction angle. As this decreases, that is, as the rectifier becomes more lightly loaded, the conduction angle decreases, I_{max} and I_{eff} (see Figure 3) go up in terms of I_o , and the voltage loss $(V_1/V_o - 1)$ goes down. ($V_1 = E_{rms}\sqrt{2}$). Ripple voltage and current formulas for various circuits are shown in Figure 3.

The data are based on the assumption of large capacitance, i.e., $CR_o > 250$, where C is in microfarads and R_o in kilohms. The calculated values of ripple voltage will tend to be higher than those observed experimentally since electrolytic capacitors generally have significantly more than rated capacitance. The calculated capacitor ripple current is that which would be measured by a thermocouple instrument connected in series with the capacitor. If the capacitor ripple current is greater than permitted, the capacitor should be paralleled by another similar unit; since capacitance values will not in general be matched, the allowable ripple current will not be quite doubled. A rating of $1\frac{1}{2}$ times the single capacitor rating would be conservative. Alternatively, or in addition, it may be desirable to increase R/R_o , and correspondingly, V_1 , to permit reduction of the ripple current (See Figure 5.) Note that, by industry practice, the allowable capacitor ripple current for a fundamental at 60 c/s is approximately 80% of the usual value for a fundamental at 120 c/s; this reduction should be applied when using half-wave or full-wave doubler circuits for which the fundamental component of the ripple is at 60 cycles.

IV. COMPARISON OF RECTIFIER CIRCUITS.

A few general comments regarding the choice of circuit are in order. No one circuit is universally preferable because each one has advantages and drawbacks. Transformer, rectifier, and filter cost all vary with the circuit chosen.

Figure 3 shows each circuit with associated data on peak inverse voltage, ripple voltage and current, rectifier surge current, and interpretation of symbols.

A. Half Wave Circuit.

The simple half-wave circuit minimizes rectifier cost, but suffers from poor transformer utilization, which results in a need for more copper to keep heating reasonable, and also requires extra filtering to keep ripple down. The half-wave circuit is primarily useful for low-current, high-voltage applications where rectifier cost is an important factor and filtering is easy because of the small load current.

B. Full-Wave Circuit.

The full-wave circuit may be regarded as two paralleled half-wave circuits operating on alternate half cycles. This circuit provides somewhat less than half the ripple voltage of the half-wave circuit. The transformer heating current is half that of the half-wave rectifier, but, if the winding is confined to the same space, the resistance through which this current passes is approximately four times that of the half-wave case, so the transformer heating is not much changed. The greater number of turns of finer wire can be expected to make for a more expensive winding. The use of two rectifiers doubles the available dc output current over the half-wave case insofar as rectifier ratings are concerned. This circuit is attractive when rectifier and filter costs are more important than optimum transformer utilization.

C. Full-Wave Doubler Circuit.

The full-wave doubler circuit may be regarded as two series-connected half-wave circuits operating on alternate half cycles. Because the same winding is used in both half cycles, the transformer utilization is improved so that transformer heating is approximately one-half of that for the half-wave case, providing the same window area was occupied by the two secondary windings. This circuit also requires only half the peak inverse voltage rating of the half-wave or full-wave rectifier circuits. It does require twice the number of filter capacitors for the same ripple as the half-wave circuit, each capacitor being of the same value as for the half-wave case but rated at half the voltage, and requires the low side of one of the capacitors to be hot to ground.

D. Bridge Circuit.

The bridge circuit may be regarded as two parallel-connected half-wave circuits operating on alternate half cycles. The transformer winding is used on both half cycles, resulting in the same efficient utilization as for the full-wave doubler. As with the full-wave doubler, the peak inverse voltage rating is half of that for the half-wave or full-wave case. Filtering is efficient, with somewhat less than half the ripple output of the half-wave case. The price to be paid is, of course, the need for four rectifiers as compared with two for the full-wave doubler. The transformer will have the same number of turns as for the half-wave case.

E. Summary.

From the foregoing, it may be seen that the full-wave doubler and the bridge both use the transformer much more efficiently than the half-wave or full-wave circuits. For equal ratios of dc output voltage to transformer secondary voltage, the transformer utilization is greater by a factor of $\sqrt{2}$ for the full-wave doubler and bridge circuits compared with half-wave or full-wave circuits. Put another way, the required window area is greater by $\sqrt{2}$ for the half-wave or full-wave circuits as compared with the full-wave doubler or bridge circuit for equal temperature rise. See also Figure 6. The choice between the full-wave doubler and the bridge is primarily a balance of rectifier-versus-filter cost.

V. DESIGN CURVES.

Figure 4 has been calculated to show a number of parameters in terms of the ratio R/R_o . While these have been derived from conduction angle as parameter, the latter disappeared in the plotting.

1. The lower four downward-sloping curves show the ratio of I_{eff} to I_o and are labeled for the conditions to which they apply. Their slope is generally $-1/6$. The lower curve gives the rms current, for the full-wave circuit, through each half of the center-tapped rectifier secondary winding. The next higher curve ($\sqrt{2}$ times as large) gives the rms current through resistor R_f of the full-wave circuit. It is also the right one for bridge-type full-wave rectifiers. The proper one of these four curves or the corresponding curve of Figure 5 should be used to determine how much copper is required in a given winding. The curves may be used to be sure that R_f is large enough to prevent excessive heating or surge currents in the rectifier. In the absence of specific rectifier ratings, the ratio of rms current in each rectifier to the rated rectifier dc should be 2.5 or less.

2. The upper three downward-sloping curves give the ratio of peak current I_{max} to I_o for the half-wave, full-wave doubler, and the full-wave and bridge cases. Their slope is generally $-1/3$. These should be consulted to be sure the peak current ratings of the rectifiers employed are not exceeded.

3. Of the six upward-sloping curves, the top one, the third one, and the fifth one (all solid-line) show, for the full-wave doubler, half-wave, and full-wave and bridge cases, respectively, the loss in voltage during the conduction angle in terms of the dc output voltage. The slope is generally $+2/3$. You will see, for instance, that for a value of R/R_o of 0.01 (commonly encountered), the peak voltage V_1 of the transformer secondary must be 17% higher than one-half of the dc output voltage in the full-wave doubler case, 11% higher than the full dc output voltage in the half-wave case, and 6.7% higher for the bridge or full-wave case (one-half secondary for this last). The moral of this is not so much that

one circuit results in more voltage loss than another, but rather that the choice of R/R_o will usually be different for each circuit.

4. In case one is interested in the watts or volt-amperes demanded from the transformer in comparison to the "useful" dc watts $V_o I_o$, the other three (second, fourth, and lowest upward-sloping curves) should be consulted. The slope of these is also generally $+2/3$. Thus, for an R/R_o of 0.01, the transformer supplies 13% more watts than the useful dc $V_o I_o$ in the full-wave doubler case, 8.4% more in the half-wave case, and 5.3% more in the bridge or full-wave cases. (While the useful dc watts are really $V_L I_o$, $V_o I_o$ is the more significant quantity, since it is not affected by the filter constants; rectifier performance should not be obscured by irrelevant variations in filters.) This is useful in helping determine, by wattage rule of thumb, what size transformer will be needed for a given power supply. The curves of Figures 6 and 7 are also useful in this connection.

Figure 5 is a replot of some of the data from Figure 4 which shows directly the ratio of rms transformer current and of peak rectifier current to direct-load current versus output voltage expressed as a percentage of the maximum attainable for the particular circuit in use. The appropriate values of R/R_o have been spotted on these curves for several typical operating points.

In some cases, a trade between transformer heating current I_{eff} and the voltage loss in current-limiting resistance $R = R_s + R_r + R_f$ may be desirable in order to wind full layers in the transformer for best space utilization.

If the proper compromise arrived at from the curves of Figure 5 is not one for which R/R_o is shown directly, the correct value for R/R_o should be determined from the curves of Figure 4, working back from the chosen value of I_{eff}/I_o . After making allowance for R_s and R_r , R_f may be determined. In making the choice of I_{eff} , any applicable limitations on allowable filter capacitor ripple current should be taken into account.

Figure 6a is a replot of the data of Figure 4 to show transformer utilization factor versus output voltage where the output voltage is expressed as a percentage of the maximum attainable for the particular circuit in use. The reciprocals of these curves, normalized to the value at optimum transformer utilization for the bridge or full-wave doubler circuit, give a measure of relative window area required of a transformer as the design departs from the optimum utilization. These are plotted in Figure 6b.

While the addition of appropriate series resistance to the rectifier circuit may result in optimum transformer utilization, the power lost in the added series resistance is significant, and the overall power-supply efficiency is less than if more transformer window area had been used to permit less external resistance. Figure 7 shows overall power-supply efficiency as a function of output voltage, neglecting transformer core loss. This indicates that, unless the

transformer is loaded to capacity, it may be preferable to use less than the optimum utilization factor in order to realize better regulation and better overall power-supply efficiency. A reduction to one-half of the optimum resistance will increase output voltage from 78% to 86% and will reduce the available output power for a given window area by only about 3%. For most cases, this is a good starting point for a practical design, the final compromise being one which allows full layers of appropriate wire size in order to make good use of the available winding space. A further 2:1 decrease to one-fourth of the optimum source resistance will increase the output voltage to 91%, and will reduce the available power by about 10%. Only in unusual cases would it be desirable to go further than this as the effective currents rise very rapidly beyond this point. When calculating open-circuit voltages using this rigorous design procedure, do not include any "rule-of-thumb" regulation allowance; disregard the paragraph on page 8 of ESPD-TR entitled "Regulation Allowance".

VI. DESIGN EXAMPLES.

EXAMPLE 1.

Output Requirements

300 v at 60 ma (18 watts) with regulation of 15% permissible, and 6.3 volts ac at 3 amperes.

Choice of Circuit

Either a voltage doubler or a bridge circuit seems reasonable for the high-voltage rectifier. Let us calculate the bridge design first.

Transformer Size

The transformer utilization for the rectifier winding is 66% (from Figure 6a), so we require a volt-ampere capacity of 27 for the 18-watt dc output. The heater winding requires 19 va, for a total of 46 va, comfortably within the 50-va average rating of a type 485 core as shown on the Winding Standards chart of ESPD-TR.

Transformer Primary

The standard split primary is suitable. Each primary consists of 7 layers of No. 28 for a pileup of 107 mils or 214 mils total, plus interwinding insulation (12 mils each) and shield for a total of 240 mils, leaving 323 mils for the secondaries.

Transformer Secondaries (Bridge Rectifier)

Assuming 15% regulation, the peak secondary voltage is:

$$V_1 = \frac{100}{85} \times 300 + 2 = 355 \text{ volts (allowing 2 volts for the}$$

forward drop of the two rectifiers in series)

$$E_{rms} = \frac{355}{\sqrt{2}} = 251, \text{ and at } 5.74 \text{ turns/volt, we require } 1440 \text{ turns.}$$

From Figure 5, we see that:

$I_{eff}/I_o = 1.83$, so that $I_{eff} = 1.83 \times 60 = 110$ ma.

At 825 circular mils per ampere, we need $825 \times .11 = 91$ circular mils. We choose No. 30 wire (100.5 cm), thus helping to make up for the usual slight deficiency in primary wire size. We require 11.6 layers, for a pileup of 155 mils.

The heater winding requires 50 turns of No. 16 wire, exactly two layers, for a pileup of 120 mils. Clearly there is plenty of space for interlayer insulation since the total secondary pileup is only 275 mils out of 323 mils available.

Rectifier Operating Conditions

Secondary resistance = 74 ohms (est.)

Reflected primary resistance = $\left(\frac{1440}{660}\right)^2 \times 10 = 48$ ohms.

Transformer resistance = 122 ohms.

From Figure 5, $R/R_o = 0.04$ for $V_o/V_1 = 85\%$;

Since $R = \frac{300 \text{ volts}}{60 \text{ ma}} = 5$ kilohms, $R_o = 200$ ohms, and we

should add an external current-limiting resistor of 78 ohms. The peak rectifier current (from Figure 5) will be $5.3 I_o = 318$ ma.

The surge current will be $\frac{355 \text{ v}}{200 \Omega} = 1.8$ amperes. The peak

inverse rating must be at least $355 \times 1.1 = 400$ volts to take care of high line conditions. The small lead-mounted rectifiers such as 2RE-1002 easily meet these requirements.

Filter Capacitor (Bridge Circuit)

For $CR_o > 250$ (where C is in μf , and R_o in kilohms), C must be at least $50 \mu\text{f}$, with a voltage rating of at least 400 volts. It must handle a ripple current of

$$I_o \times \sqrt{\left(\frac{I_{eff}}{I_o}\right)^2 - 1} = 60 \times \sqrt{(1.83)^2 - 1} = 92 \text{ ma.}$$

(from Figure 3)

The large section of a COE-10 offers $50 \mu\text{f}$ at a working voltage of 450 volts and a ripple current rating of 375 mils and is, therefore, quite adequate. The peak-to-peak

ripple voltage will be (from Figure 3) $\frac{750}{CR_o}$ % of V_o or 3% of 300 volts = 9 volts, but this can readily be reduced 2:1 by using all sections of the COE-10 in parallel to give $C = 100 \mu\text{f}$.

Alternative Voltage-Doubler Design

At the present time, rectifier prices are so low that the two extra rectifiers in the bridge circuit are usually less expensive and certainly smaller than the extra filter capacitor required by the voltage doubler, but it is interesting to summarize the results of calculations for the latter case. Based on the 15% regulation requirement, $R/R_o = 0.01$, $I_{eff}/I_o = 3.7$, for $I_{eff} = 222$ ma, just twice the

value for the bridge design. The peak voltage of 176 volts (124-v rms) is half that for the bridge design.

The transformer secondary would consist of 712 turns of No. 27 wire, eight full layers, for a pileup of 154 mils, identical to the bridge design. The transformer resistance = 20 ohms (secondary) + 12 ohms (reflected primary).

Since the desired value of $R = 50 \Omega$ ($R/R_o = 0.01$), an 18-ohm external series resistor would be required. The rectifier peak inverse rating is $1.1 \left(\frac{V_o}{2} + V_1\right) = 1.1 \times (150 + 176) = 360$ volts, little changed from the bridge design. The same 2RE-1002 rectifiers will be suitable.

The filter capacitors should have twice the capacitance of those for the bridge circuit, but need only half the voltage rating. A pair of COE-88 would be suitable ($100 \mu\text{f}$, 200-v dc) but ripple would be double that for the bridge circuit using the whole COE-10, and safety margin on voltage would be minimal. A pair of COE-41 ($160 \mu\text{f}$, 300-v dc) would be preferable, though ripple would still be 25% higher than for the bridge circuit example.

EXAMPLE 2.

Output Requirements

30 volts dc at 3 amperes (90 watts), with 10% regulation.

Choice of Circuit

The logical choice is a bridge rectifier since good low voltage, high-current rectifiers are reasonable in cost and small in size. The only other circuit which utilizes the transformer efficiently is the voltage doubler, which would require more costly filter capacitors.

Transformer Size

For a single secondary, we should be able to approximate an optimum design. From Figure 6a, we find that transformer utilization at 10% regulation = 63%. The 365 core with an optimum rating of 150 va could give up to 95 watts at 63% utilization, so we might be able to get the desired 90 watts of dc.

Transformer Primary

At this high utilization we will require an optimum rather than standard primary, wound in such fashion as to leave maximum space for copper in the secondary. The 413 turns of recommended No. 23 wire for each split primary require 5.24 layers. By winding the fractional layers of each primary adjacent to each other, the whole primary can be put in 11 layers for a total of 330 mils including interlayer insulation, thus leaving 360 mils available for the secondary. Note that even the "optimum" primary is about one wire size small since at 150 va, we would have

$\frac{150}{115} = 1.3$ amperes, requiring 1300 circular mils or a pair

of No. 22 primaries. Use of No. 22 wire would result in a pileup of 390 mils including interlayer insulation, which is more than half the allowable pileup, and would not leave adequate room for the secondary. Actually, this deviation from the nominal cross-sectional requirement is probably acceptable because the primary, being close to the core material, can dissipate its heat more effectively than can the secondary. It behooves us, however, to provide some extra secondary capacity if we are to keep the operating temperature under control. On a tight design such as this, the final acceptability is based on a winding temperature not to exceed 105°C under the least favorable line and ambient conditions; this should be verified by actual test.

Transformer Secondary

Assuming 10% regulation, the peak secondary voltage V_1 is 33.3 volts plus 2.4 volts to allow for the forward drop of two rectifiers, or 35.7 volts peak, 25.3 volts rms. At 3.59 turns/volt, we require 91 turns. From Figure 5, we see that $I_{eff}/I_o = 2.03$, so we require 6090 circular mils. In view of the marginal primary, we should try for extra secondary copper to improve the average, and note that size B rectangular wire offers 7060 circular mils. We can get up to 96 turns in 6 layers for a pileup of 342 mils, so we can get the 91 turns in with some margin in case the allotment for rectifier drop turns out too low.

Rectifier Operating Conditions

Secondary resistance (91 turns of "B") = 0.097 ohm

Reflected primary resistance $\left(\frac{91}{413}\right)^2 \times 2.53 = 0.123$ ohm

Transformer resistance = 0.220 ohm

For 10% regulation, $R/R_o = 0.021$; since $R_o = 10$ ohms, $R = 0.21$ ohm desired versus 0.22 ohm already in the transformer. Clearly no external series resistor is required.

$I_{eff}/I_o = 2.03$, hence $I_{eff} = 6.1$ amperes

$I_{max}/I_o = 5.25$, hence $I_{max} = 15.8$ amperes (peak rectifier current)

$I_{surge} = \frac{35.7 \text{ v}}{0.22 \Omega} = 162$ amperes.

Peak inverse voltage = $36 \times 1.1 = 40$ volts (allowing for high line). These ratings are readily provided by the low-cost type 2RE-1005 and -1006 (IN3492 and IN3492R) rectifiers.

Filter Capacitor

For $CR_o > 250$ (where C is in microfarads and R_o in kilohms), C must be at least 25,000 microfarads.

The dc working voltage should be 40 volts, with correspondingly higher surge voltage rating. It must handle a ripple current of $1.77 I_o$ or 5.3 amperes. Since the largest preferred capacitor of adequate voltage ratings has only 2400 μf capacitance (COE-82), a large can unit such as Aerovox 61QE3189M (3" dia. \times 4-5/8" high, similar to COE-67 in size) with a capacitance of 24,400 μf , a working voltage rating of 40 volts, a surge rating of 60 volts, and a ripple current rating of 5.98 amperes should probably be employed.

The peak-to-peak ripple voltage will be $\frac{750}{CR_o}$ % of V_o (from Figure 3) = 3% of 30 volts = 0.9 volt.

HALF WAVE

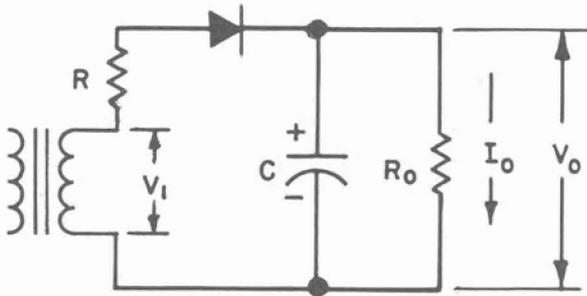


Figure 3a.

Peak inverse voltage on rectifier = $V_o + V_1$

For 60-cycle line frequency:

$$\frac{\text{r-m-s ripple}}{V_o} \approx \frac{440}{CR_o} \%$$

$$\frac{\text{peak-to-peak ripple}}{V_o} \approx \frac{1500}{CR_o} \%$$

$$\text{peak-to-peak ripple volts} \approx 15 \frac{I_o}{C}$$

$$\frac{\text{r-m-s capacitor ripple current}}{I_o} = \sqrt{\left(\frac{I_{eff}}{I_o}\right)^2 - 1}$$

(fundamental frequency is 60 cycles)

FULL WAVE

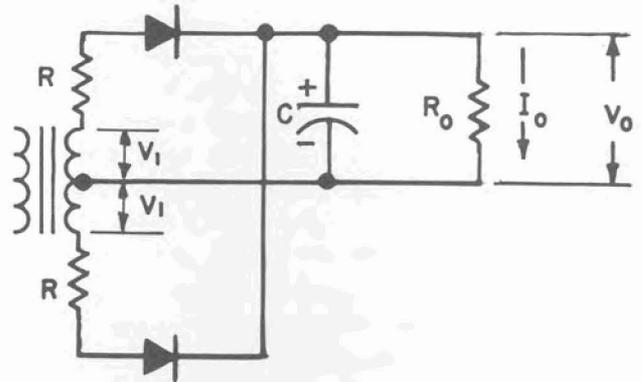


Figure 3b.

Peak inverse voltage on rectifier = $V_o + V_1$

For 60-cycle line frequency:

$$\frac{\text{r-m-s ripple}}{V_o} \approx \frac{220}{CR_o} \%$$

$$\frac{\text{peak-to-peak ripple}}{V_o} \approx \frac{750}{CR_o} \%$$

$$\text{peak-to-peak ripple volts} \approx 7.5 \frac{I_o}{C}$$

$$\frac{\text{r-m-s capacitor ripple current}}{I_o} = \sqrt{2 \left(\frac{I_{eff}}{I_o}\right)^2 - 1}$$

(fundamental frequency is 120 cycles)

R_s = resistance of one-half of secondary, including reflected primary resistance.

R_r = resistance of one rectifier

R_f can be in the center tap return and of the same value as each separate resistor.

ripple factor: 0.25×10000

Figure 3. Rectifier circuits with large capacitance ($CR_o > 250$) input filter.

$(\mu F)(K\Omega)$

FULL-WAVE DOUBLER

BRIDGE

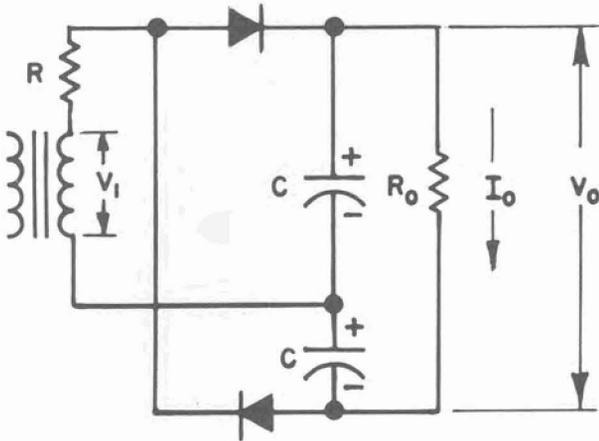


Figure 3c.

Peak inverse voltage on rectifier = $V_o/2 + V_1$

For 60-cycle line frequency:

$$\frac{\text{r-m-s ripple}}{V_o} \approx \frac{440}{CR_o} \%$$

$$\frac{\text{peak-to-peak ripple}}{V_o} \approx \frac{1500}{CR_o} \%$$

$$\text{peak-to-peak ripple volts} \approx 15 \frac{I_o}{C}$$

$$\frac{\text{r-m-s capacitor ripple current}}{I_o} = \sqrt{\frac{1}{2} \left(\frac{I_{eff}}{I_o} \right)^2 - 1}$$

(fundamental frequency is 60 cycles)

R_r = resistance of one rectifier

r-m-s current in rectifier = $0.707 \times I_{eff}$

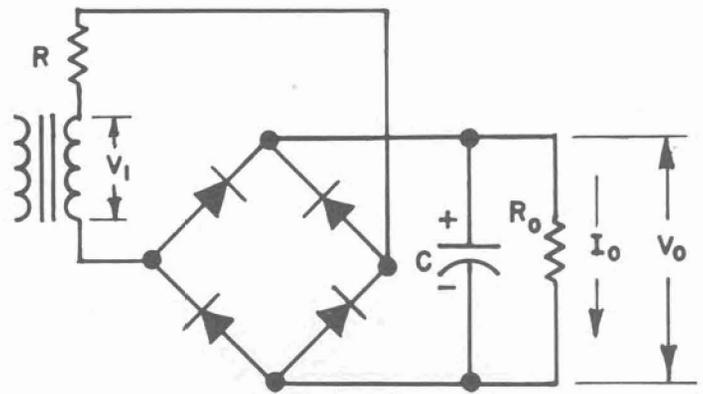


Figure 3d.

Peak inverse voltage on rectifier = V_1

For 60-cycle line frequency:

$$\frac{\text{r-m-s ripple}}{V_o} \approx \frac{220}{CR_o} \%$$

$$\frac{\text{peak-to-peak ripple}}{V_o} \approx \frac{750}{CR_o} \%$$

$$\text{peak-to-peak ripple volts} \approx 7.5 \frac{I_o}{C}$$

$$\frac{\text{r-m-s capacitor ripple current}}{I_o} = \sqrt{\left(\frac{I_{eff}}{I_o} \right)^2 - 1}$$

(fundamental frequency is 120 cycles)

R_r = resistance of two rectifiers in series

r-m-s current in rectifier = $0.707 \times I_{eff}$

FOR ALL CIRCUITS

C is in mfd, I_{eff} is r-m-s current in transformer secondary, I_o is in ma, R_o is in kilohms, V_1 = peak open-circuit voltage.

$R = R_f + R_r + R_s$ where: R_f = current-limiting feed resistor

R_r = rectifier forward resistance

R_s = resistance of transformer secondary + reflected primary resistance

Rectifier transient switching surge current = V_1/R (worst case).

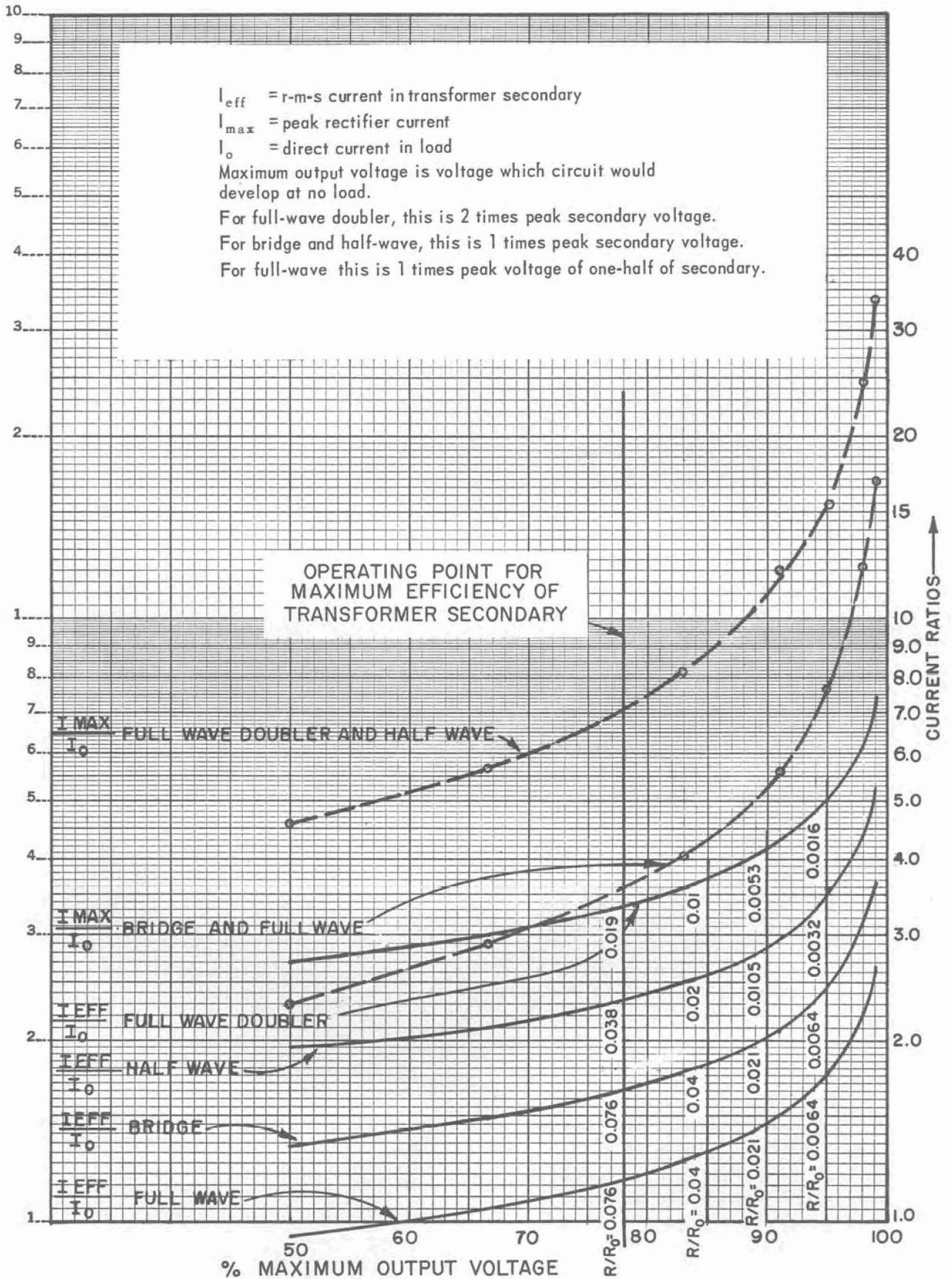


Figure 5. Current ratios versus voltage ratio.

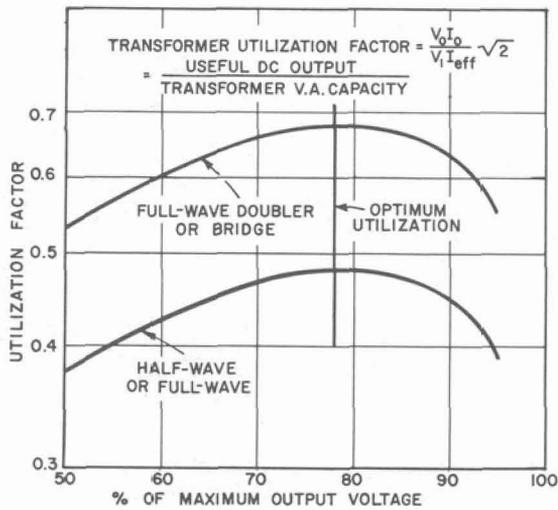


Figure 6a. Transformer utilization factor versus voltage ratio.

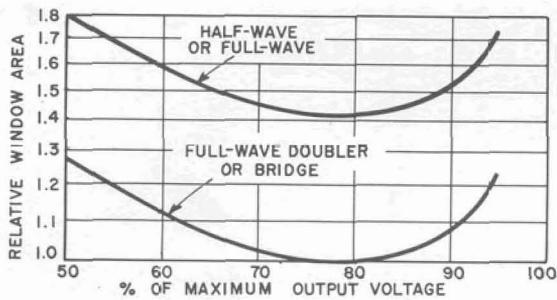


Figure 6b. Window utilization versus voltage ratio.

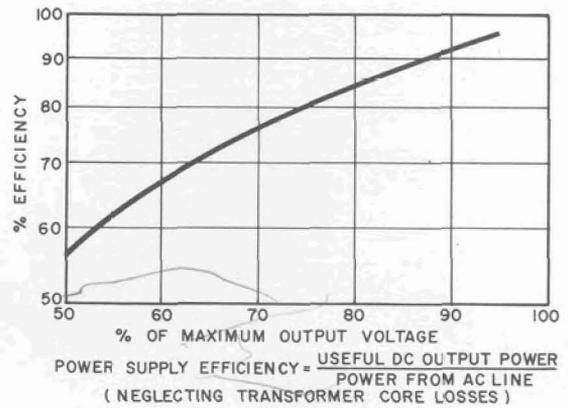


Figure 7. Power supply efficiency versus voltage ratio.

G E N E R A L R A D I O C O M P A N Y
 WEST CONCORD, MASSACHUSETTS, USA