CHAPTER 30

RECTIFICATION

By R. J. Rawlings, Grad. I.E.E., Associate Brit. I.R.E.
and F. Langford-Smith, B.Sc., B.E.

SECTION 1 : INTRODUCTION TO RECTIFICATION

(i) Principles of rectification (ii) Rectifier valves and types of service (iii) The use of the published curves (iv) Selenium and copper-oxide rectifiers.

(i) Principles of rectification

Most electronic equipment requires some form of plate voltage supply which has in the majority of cases to be derived from single-phase a.c. mains. It is the purpose of this chapter to outline the principles and calculations involved, with particular reference to those types of supply required for radio receivers and amplifiers.

The most general and accepted method of a.c. to d.c. conversion, where very large amounts of power are not required, is by valve rectifiers of either the high vacuum or mercury vapour type. Selenium and copper-oxide rectifiers are also used—see (iv) below.

Diagram A in Fig. 30.1 shows a sine wave voltage of which the peak and r.m.s. values are shown as $\hat{E}_{\sim}$ and $|E_{\sim}|$. With ideal half-wave rectification and a resistive load with no filter, the positive or upper peaks would also represent the load current, while the negative or lower peaks would be suppressed ; the average voltage would be shown by E_{dc} in the half-wave case. With full-wave rectification the current through the load resistance would be similar* each half cycle, the lower peak being replaced by the dashed line in A. The direct voltage would be the average voltage, i.e., 0.9 of the r.m.s. voltage for a sine wave. For half-wave rectification the average direct voltage over a period would be one half that for full-wave rectification under the same conditions.

Fig. 30.1B illustrates **ideal full-wave† rectification with a condenser input filter** (circuit as Fig. 30.1F in which choke L is assumed to have very high inductance and zero resistance). The voltage at the first filter condenser C_1 follows the line ABA′B′, the condenser charging between A and B but discharging between B and A′.

---

*In practice there is always some lack of symmetry caused by a combination of small factors such as the use of one end of the filament as cathode return in place of a centre-tap, variations in characteristics between the two units in the rectifier and variations in transformer secondary voltages and impedances on both sides of the centre-tap. As a result there is usually a substantial amount of mains frequency ripple with full-wave rectification, although the twice-mains-frequency ripple voltage predominates.

†Also known as biphase half-wave.

Fig. 30.1. (A, B, C *&* D). *Voltage and current waveforms of condenser input and choke input rectifier systems. The symbols on the left are those used in Section 2.*

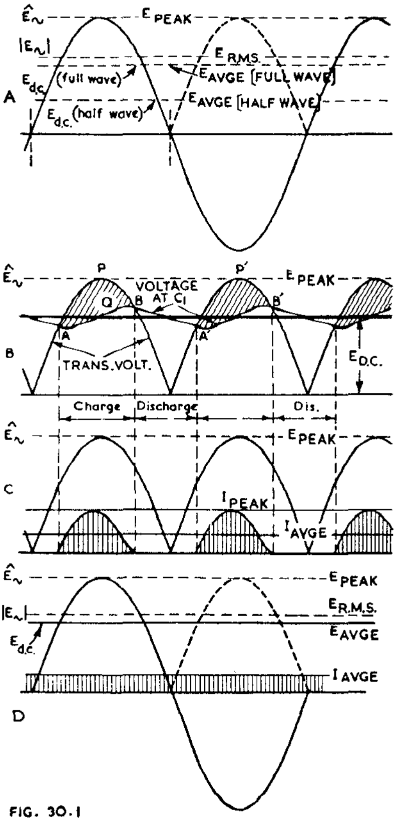


FIG. 30.1

The mean level of ABA′B′ is the effective direct voltage. The shaded area above the curve AQB represents the voltage by which the transformer voltage exceeds that of C_1. The current through the plate circuit of the rectifier only flows for the interval between A and B and between A′ and B′ because at other parts of the cycle the transformer voltage is below the voltage of C_1. The current through the rectifier, shown in Fig. 30.1C, is similar in form to the difference in voltage between the curves APB and AQB in Fig. 30.1B.

The ripple voltage may be determined from the ABA′B′ curve, and the values of the fundamental and harmonics may be determined by a Fourier analysis.

As the load resistance (R_L in Fig. 30.1F) is increased, BA′ becomes more nearly horizontal and the area APB becomes smaller until in the extreme (theoretical) case when the load resistance is infinite the direct voltage is equal to the peak voltage. This graphical method may be applied to any rectifier with a condenser input filter followed by a high inductance choke. The assumption is made that the current through the inductance remains constant, that is to say that the lines BA′, B′A″ etc. are straight.

With a (full wave) **choke input filter*** the conditions are as shown in Fig. 30.1D assuming a very high inductance choke (L_1 in Fig. 30.1G), although with practical chokes there will necessarily be a certain amount of ripple in the load current.

---

* The term "choke input" is used for convenience in this Handbook to indicate a series inductance followed by a capacitance shunted across the load resistance.

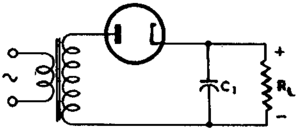


FIG. 30.1E

Fig. 30.1E. *Basic circuit diagram of half-wave rectifier with condenser input filter.*

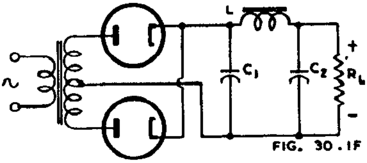


FIG. 30.1F

Fig. 30.1F. *Basic circuit diagram of full-wave rectifier with condenser input filter.*

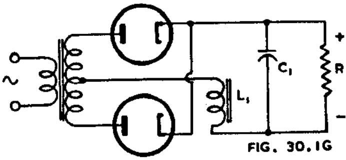


FIG. 30.1G

Fig. 30.1G. *Basic circuit diagram of full-wave rectifier with choke input filter.*

Maximum ratings

Rectifier valves are usually rated for maximum direct-current per plate, maximum peak current per plate, maximum peak inverse plate voltage and maximum r.m.s. supply voltage per plate. In some cases a maximum rated hot-switching transient (or surge) plate current per plate (for a specified maximum time, e.g. 0.2 second) is also given. It is important to ensure that no one of these ratings is exceeded under the conditions of operation. If the ratings are design centre values—see pages 77 and 78—they apply to nominal mains voltages.

Maximum direct current per plate

This may be measured by a d.c. milliammeter in series with R_L (Figs. 30.1 E, F or G).

Maximum peak current per plate

This may either be measured by means of a C.R.O. or calculated by the method described in Section 2 or 3 for condenser or choke input respectively. It is largely influenced by the total effective plate supply impedance per plate, and in any case where the peak current is too high, it may be reduced by adding a resistor in series with each plate or by increasing the effective impedance of the transformer to give the same result. The method of calculating the plate supply impedance per plate for a transformer is given on page 99. In cases where no transformer is used, as in a.c./d.c. receivers, a resistor should be connected in the plate circuit to limit the peak current to a safe value. It is good practice in all cases to limit the peak current to a value below the maximum rated value, to give a margin for safety and longer life.

Maximum peak inverse plate voltage

This is 1.41 times the r.m.s. voltage of the whole secondary winding of the transformer in Fig. 30.1F or G, and twice this value in Fig. 30.1E.

Maximum r.m.s. supply voltage per plate

A higher r.m.s. supply voltage is usually permitted with a choke input to the filter than with condenser input to the filter. In some cases, with a condenser input to the filter, a higher r.m.s. supply voltage per plate is permitted provided that the direct plate current is reduced below its maximum rating and that the total effective plate supply impedance per plate is increased for the higher voltage conditions (e.g. Fig. 30.2A). With a choke input to the filter, the maximum r.m.s. supply voltage per plate is sometimes only permissible provided that the direct plate current is reduced below its maximum rating (e.g. Fig. 30.2C). With a choke input to the filter, it is essential to have a **choke inductance** not less than the critical value for the particular operating condition in question. The critical inductance is a function of the load resistance and the frequency of the supply, as given by eqns. (1), (2) and (3) in Sect. 3.

For any value of inductance, with constant r.m.s. supply voltage, there is a value of current below which operation is not permitted. This is shown in Fig. 30.2C where boundary lines for choke sizes are included.

Equivalent circuit of high vacuum rectifier

The high vacuum rectifier can be considered as being an ideal switch in series with a non-linear resistance and a source of potential which is connected by the switch to the load when the polarity is that required by the load (Ref. 7). As the switching gives rise to pulsating currents (and voltages) it is necessary to assume a linear resistance which is equivalent to the non-linear effective resistance of the rectifier during this pulsating or conduction period. The conduction period (ϕ), and therefore also the magnitude of the current pulse, will depend on the loading and the type of filter connected to the rectified supply. Certain approximations which must be made for the first calculation should be readjusted when the results are known, in order that a second and more accurate calculation can be made.

Mercury vapour rectifiers

In the case of mercury vapour rectifiers the voltage drop in the valve is a constant value of the order of 10 to 15 volts over a wide range of currents. These rectifiers are generally used with choke input filters to provide good regulation for class B amplifiers.

The direct voltage output of such a system is equal to 0.9 times the r.m.s. value of the input voltage minus the valve voltage drop—

e.g. Output voltage $= (0.9\ E_{rms} - 15)$ volts.

(ii) Rectifier valves and types of service

Rectifier valves may be subdivided into the following groups :—

(1) High vacuum (a) High impedance (e.g. 5Y3-GT)
    (b) Medium impedance (e.g. 6X4, 5R4-GY)
    (c) Low impedance (e.g. 5V4-G, 35Z5-GT)

(2) Mercury vapour—(e.g. 82, 83).

The choice of a rectifier valve for a particular service must take into account the maximum permissible ratings for peak current, average current, and peak inverse voltage. The design of the following filter will influence these last two factors particularly ; the type of filter, either choke or condenser input, will be determined partly by the demands of power supply regulation. In supplies feeding Class A output stages the choice will probably be a condenser input filter, but where Class AB_1 and AB_2 output stages are to be supplied, the regulation of the power supply becomes a significant feature and choke input filters with low impedance rectifiers must be used.

The following examples represent typical practice—

A.C. radio receivers with Class A power stage :—

High vacuum full wave (e.g. 6X4, 5Y3-GT, 5U4-G).

A.C. radio receivers with Class AB_1 power stage :—

With self bias—high vacuum full wave (e.g. 5Y3-GT, 5U4-G, 5R4-GY, 5V4-G)

With fixed bias—low impedance high vacuum full wave (e.g. 5V4-G).

A.C./D.C. radio receivers :—

Indirectly-heated low impedance high vacuum half-wave types with heaters operating at 0.3 A or 0.15 A (e.g. 25Z6-GT or 35Z5-GT).

In England, heaters operating at 100 mA are widely used.

Battery operated radio receivers with non-synchronous vibrators :—

Indirectly-heated low or medium impedance high vacuum full-wave types (e.g. 6X4).

Amplifiers :—

As for radio receivers except that mercury vapour types may also be used.

In general for radio receiver and small amplifier design high vacuum rectifiers are to be preferred to mercury vapour types because of—

1. long and trouble-free service ;
2. the lower transformer voltage which can be used for the same d.c. output voltage when a condenser input filter may be used ;
3. self protection against accidental over-load due to the fairly high internal impedance of the rectifier. Use can only be made of this last point when the supply is for use with a Class A output stage, when good regulation is not a major consideration and a high impedance rectifier may be used.

With directly-heated rectifiers it is generally found preferable to connect the positive supply lead to one side of the filament rather than to add the further complication of a centre-tap on the filament circuit.

Parallel operation of similar types of vacuum rectifiers is possible but it is preferable to connect together the two sections of a single full wave rectifier and to use a second similar valve as the other half-rectifier if full-wave rectification is required. With low impedance rectifiers as used in a.c./d.c. receivers (e.g. 25Z6-GT) it is desirable to limit the peak current by some series resistance. When two units are connected in parallel it is also desirable to obtain equal sharing, and in such cases a resistance of 50 or 100 ohms should be connected in series with each plate, then the two units are connected in parallel.

Mercury vapour rectifiers may only be connected in parallel if a resistance sufficient to give a voltage drop of about 25 volts is connected in series with each plate, in order to secure equal sharing of the load current.

(iii) The use of the published curves

From published curves on rectifier valves it is possible to predict the output voltage of a rectifier system when provided with the knowledge of the transformer voltage. For this purpose, use may be made of either the constant voltage curves or the constant current curves.

A family of curves is normally published both for condenser-input and for choke-input filters. In the former case the source impedance must be known ; it is usually published as the total effective plate supply impedance per plate.

An example of constant voltage curves, in this case applying to a condenser-input filter, is given in Fig. 30.2A. Each curve is for a specified constant supply voltage per plate ; for intermediate voltages it is possible to interpolate with sufficient accuracy.

In this particular case there is the rather unusual feature of one value of total effective plate supply impedance per plate for the lower voltage curves (1 to 5) and a higher value for the higher voltage curves (6 to 8). It is always permissible to adopt a higher value of total effective plate supply voltage per plate than that shown on the curves, but the direct voltage output will thereby be decreased somewhat. Operation is only permissible on, and below, the line formed by the highest curve and the " current and voltage boundary line " ADK. These curves only apply to one specified value of capacitance input to the filter, in this case 10 μF.

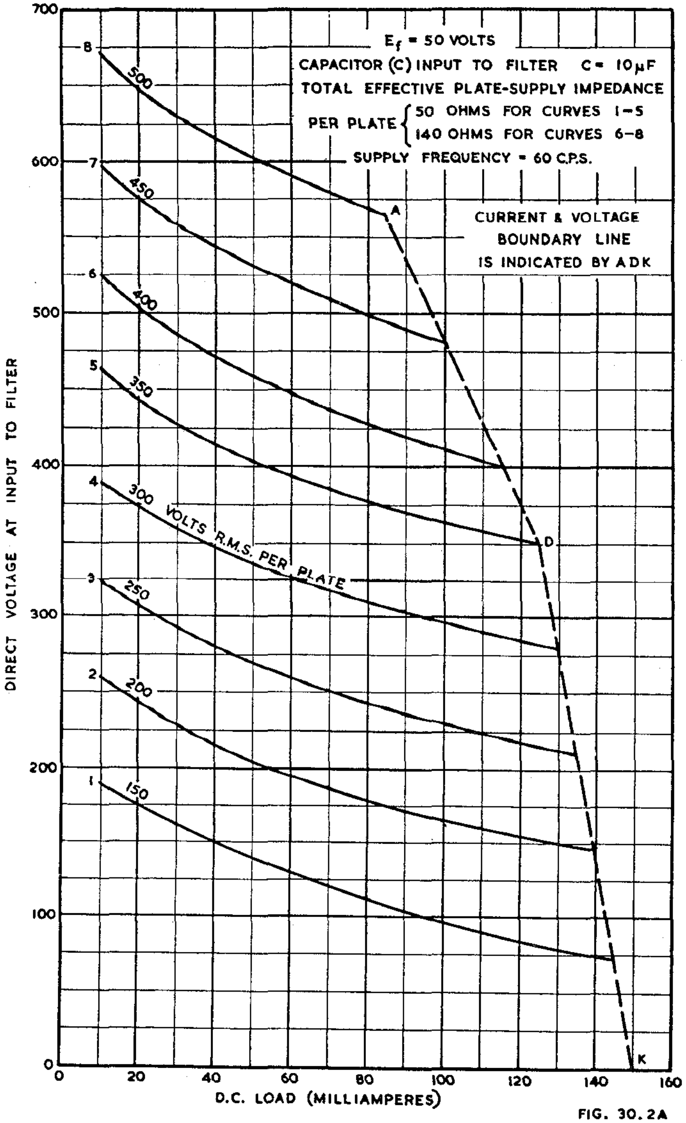


FIG. 30.2A

Fig. 30.2A. *Operation characteristics for a typical full-wave rectifier (5Y3-GT) with condenser input filter.*

The effect of change in the value of capacitance input to the filter is indicated typically by Fig. 30.2B, where curves for 3 values of capacitance are drawn. A higher capacitance gives better regulation and a higher output voltage, but increase in capacitance beyond a certain value (here about 16 μF) has only a very slight effect. If curves are only drawn for one specified value of input capacitance, operation with a higher value is not permissible unless this has been demonstrated by measurement or calculation to be within the peak current rating of the rectifier.

Curves for a typical full wave rectifier with choke input are given in Fig. 30.2C. Operation is only permissible in the area to the right of the boundary line corresponding to the proposed choke size, to the left of the current and voltage boundary line CEK, and below the highest curve for a choke of infinite inductance. If the direct current varies between two limits, it is important to select a value of inductance at least equal to, or preferably higher than, the value required for the lower limit of direct current; the inductance should be measured at the lower limit of direct current.

The constant current curves (of which an example is given in Fig. 30.3) are very helpful for deriving certain information. If it is required to find the input voltage

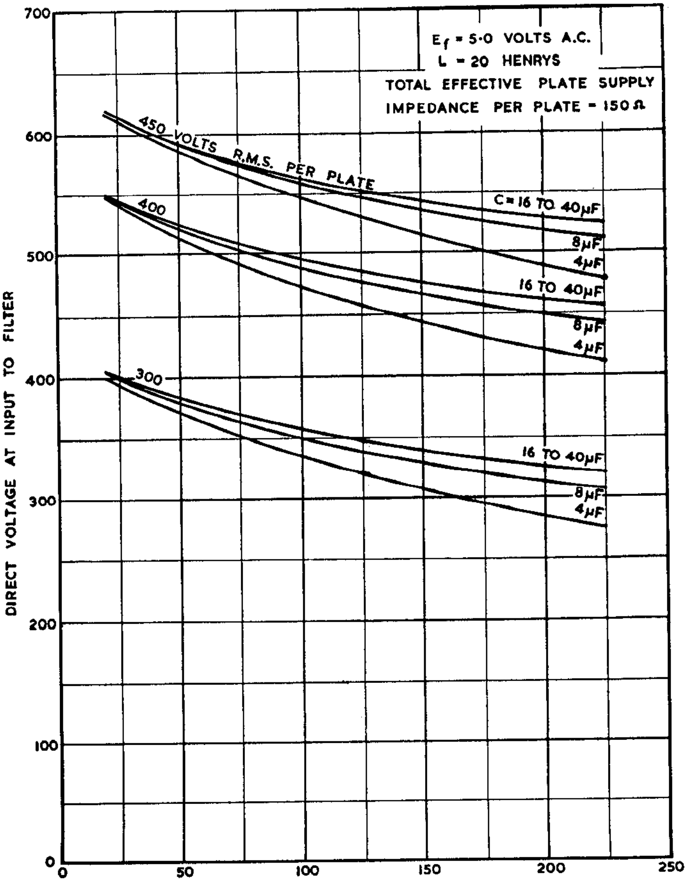


Fig. 30.2B. Operation characteristics for a typical full-wave rectifier (5T4) with condenser input filter, showing effect of input capacitance (C).

to give 250 volts 100 mA direct current, a vertical is drawn upwards from an output voltage of 250 volts to point P on the 100 mA curve. From here a horizontal line is drawn which intersects the vertical axis at 277 volts, which is the desired value.

The line OD is for equal input and output voltages. Above and to the left of this line the output voltage is less than the input voltage ; below and to the right of this line the output voltage is greater than the input voltage.

Each of the points A, B, C etc. at which the several current lines cut the vertical axis indicates the combined effective voltage drop in the valve and the transformer ;

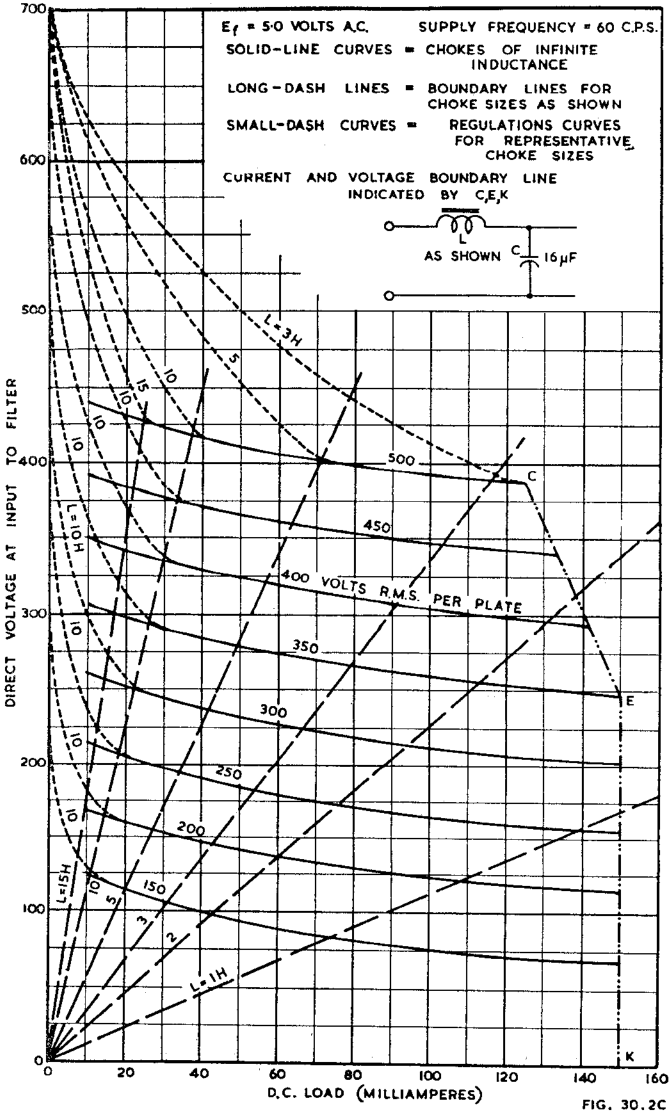


FIG. 30.2C

Fig. 30.2C. Operation characteristics for a typical full wave rectifier (5Y3-GT) with choke input filter.

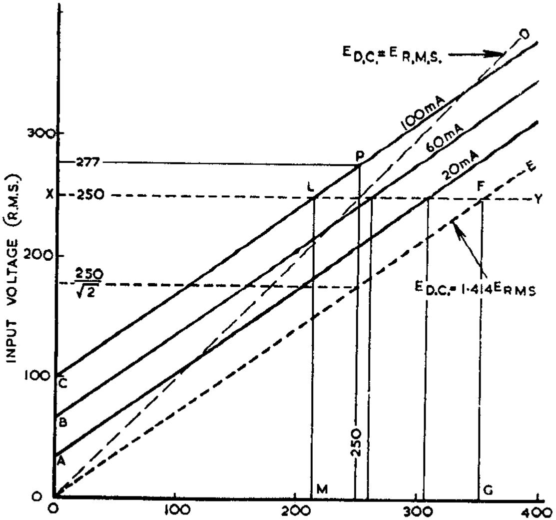


FIG. 30.3

Fig. 30.3. *Constant current curves for a* 5*Y*3-*GT rectifier* ; *condenser-input filter with capitance* 8μ*F and effective plate supply impedance* 80 *ohms per plate.*

in other words it is the input voltage required to maintain the specified load current with the load terminals short-circuited.

The line OE is the theoretical limit of output voltage with no load-current, and is drawn to correspond to an output voltage of 1.414 times the r.m.s. input voltage.

The regulation of the output voltage with varying load currents is indicated by Fig. 30.3. If the input voltage is 250 volts, a horizontal line may be drawn as in XY and vertical lines may be drawn at each intersection with the constant current curves. Line FG is for no load-current, while LM is for 100 mA load current. For this example the output voltage will be seen to drop from 354 volts at no load-current to 213 volts at 100 mA load-current.

It should be noted that the results given by any form of valve curves are only correct for the set of conditions for which the curves were derived.

(iv) Selenium and copper oxide rectifiers

Selenium and copper oxide rectifiers have been used for miscellaneous applications such as for grid bias supplies and instrument rectifiers. Recently, selenium rectifiers have been widely used as plate supply rectifiers in radio receivers.

Both types differ from thermionic rectifiers in that they have appreciable reverse current. When used within their ratings, selenium rectifiers normally have a long life, although a small percentage of breakdowns occurs throughout life.

Copper oxide rectifiers are limited to a temperature rise of about 15°C while selenium rectifiers may be operated at higher temperatures. Selenium rectifiers are smaller and lighter than copper oxide types, for the same operating conditions.

For further information see Refs. 14, 17, 21, 23, 24, 25, 26, 33.

SECTION 2: RECTIFICATION WITH CONDENSER INPUT FILTER

(i) Symbols (ii) Rectification with condenser input filter (iii) To determine peak and average diode currents (iv) To determine ripple percentage (v) To determine the transformer secondary r.m.s. current (vi) Procedure when complete published data are not available (vii) Approximations when the capacitance is large (viii) Peak hot-switching transient plate current (ix) The effect of ripple.

(i) Symbols and definitions

$\hat{r}_d$	Effective peak resistance of diode, defined as the anode voltage at the conduction peak divided by the anode current at that time.
$\bar{r}_d$	Effective average resistance of diode, defined as the average anode voltage during the conduction period divided by the average anode current during that time.
$\lvert r_d \rvert$	Effective r.m.s. resistance of diode, defined as the diode anode dissipation divided by the square of the r.m.s. anode current.
R_s	Total resistance in series with diode including transformer winding resistance and any series resistance added to limit the diode peak current.
$\hat{R}_s$	Equal to $\hat{r}_d + R_s$
$\bar{R}_s$	Equal to $\bar{r}_d + R_s$
$\hat{i}_d$	Peak diode current (one anode)
$\bar{i}_d$	Average diode current (one anode)
$\lvert i_d \rvert$	r.m.s. diode current (one anode)
$\hat{e}_d$	Diode anode voltage at peak of conduction period
R_L	Load resistance presented to rectified supply
I_L	Load current from rectified supply
E_{dc}	Rectified direct output voltage across load resistance
$\hat{E}_{\sim}$	Peak value of alternating input voltage to rectifier
$\lvert E_{\sim} \rvert$	R.M.S. value of alternating input voltage to rectifier
C	Capacitance of first filter capacitor in farads
ω	$2\pi \times$ supply frequency in c/s
$\lvert E_R \rvert$	R.M.S. value of ripple voltage existing across condenser C
E_p	Peak-inverse voltage across diode
$\lvert I_R \rvert$	R.M.S. value of ripple current through condenser C

$$\frac{|E_R|}{E_{dc}} = \frac{\text{r.m.s. ripple voltage}}{\text{direct voltage across load}} = \text{ripple factor.}$$

$$|R_s| = |r_d| + R_s.$$

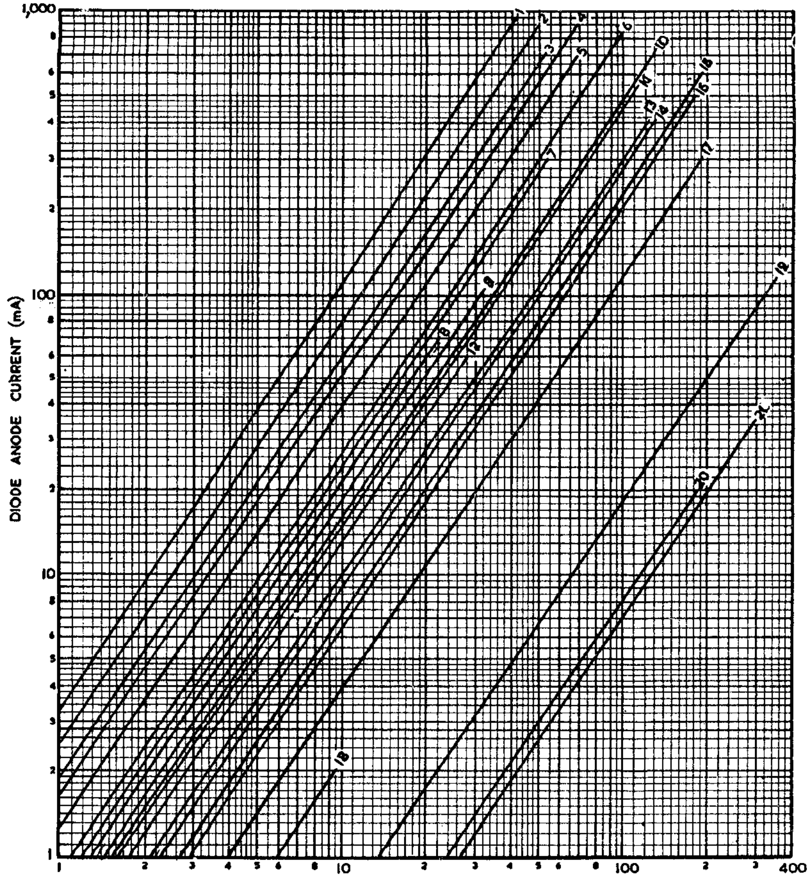
(ii) Rectification with condenser input filter

It has been stated in Sect. 1(i) that the nature of the rectified current is pulsating and that it is necessary for the purpose of this simple equivalent circuit to convert the non-linear resistance of the diode to an equivalent linear resistance. For condenser input filters it can be shown (Ref. 6) that the relationship :—

$$\hat{r}_d = 0.88\,\bar{r}_d = 0.93|r_d|$$

is correct within 5% for all circuits of this type and from the following graphs it is possible to assess the characteristics of a condenser input rectifier system.

Fig. 30.4 gives curves for a number of high vacuum rectifiers from which values of their peak resistance $\hat{r}_d$ can be found. Figs. 30.5—30.7 (based on Schade, Ref. 6)



DIODE ANODE VOLTAGE FIG. 30. 4

Fig. 30.4. Average anode characteristics of some rectifier valves (based on Ref. 6, with additions). The value of r_d for any rectifier at any diode current may be determined by dividing the diode anode voltage by the diode current.

Valve	*Curve*	*Valve*	*Curve*	*Valve*	*Curve*	*Valve*	*Curve*
1*A*3	10	6*AQ*6	19	6*W*4-*GT*	2	35*Z*5-*GT*	2
1*B*3-*GT*/8016	21	6*AR*7-*GT*	18	6*X*4	8	45*Z*3	17
1-*V*	7	6*AT*6	19	6*X*5*	7	45*Z*5-*GT*	1
2*X*2-*A*	19	6*AV*6	18	6*ZY*5-*G*	9	50*Y*6-*GT*	4
5*R*4-*GY*	11	6*B*6-*G*	18	7*B*6	18	80	14
5*T*4	6	6*B*8*	18	7*C*6	18	81	16
5*U*4-*G*	10	6*G*8-*G*	18	7*E*6	18	83*V*	4
5*V*4-*G*	4	6*H*6*	12	7*E*7	18	84/6*Z*4	7
5*W*4*	13	6*Q*7*	18	12*Z*3	4	117*N*7-*GT*	2
5*X*4-*G*	10	6*R*7*	18	25*Y*5	9	117*Z*3	3
5*Y*3-*GT*	14	6*SF*7*	18	25*Z*5	4	117*Z*6-*GT*	3
5*Y*4-*G*	14	6*SQ*7*	18	25*Z*6*	4	217-*C*	16
5*Z*3	10	6*SR*7*	18	35*W*4	2	836	6
5*Z*4*	5	6*ST*7*	18	35*Z*3	15	878	20
6*AL*5	3	6*SZ*7*	18	35*Z*4-*GT*	2		

**Includes G or GT equivalents.*

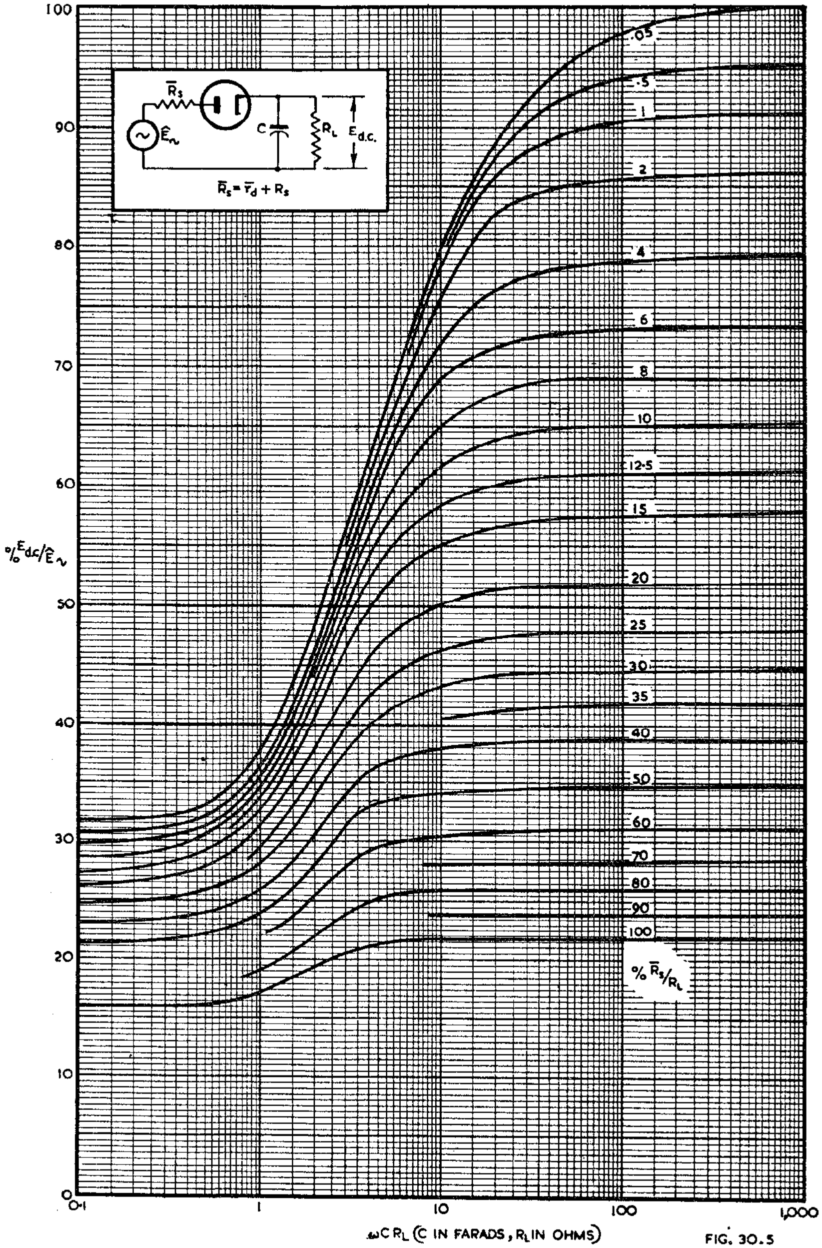


FIG. 30.5

Fig. 30.5. Ratio of rectified (direct) output voltage to peak a.c. rectifier input voltage expressed as a percentage, as a function of $\omega C R_L$ for a half-wave rectifier with a condenser input filter (Ref. 6).

are curves from which can be found the relationship between E_{dc} and $\hat{E}_{\sim}$ for half-wave, full-wave and full-wave voltage doubler circuits in terms of other circuit parameters. Curves of the ratios of effective $|i_d|$ and peak $\hat{i}_d$ diode currents to the direct current per anode $\bar{i}_d$ are given in Fig. 30.8 ; Fig. 30.9 gives details of the ripple factor and Fig. 30.10, the peak inverse voltage (all based on Ref. 6).

The design considerations to be borne in mind when using these curves are :—

(1) The value of the capacitance C is usually chosen with regard to the maximum permissible ripple in the output (see below) but if $|E_{\sim}|$ is limited to a certain value and the maximum E_{dc} is to be achieved, C may be increased above this value. In doing this due regard must be given to the maximum permissible peak current of the rectifier and, if necessary, limiting resistors placed in series with the anodes of the rectifier.

(2) In order that the direct voltage should not be closely dependent upon the value of C, the value of ωCR_L must be on or to the right of the knee of the appropriate curve in Fig. 30.5, 30.6 or 30.7 as required by the type of rectification.

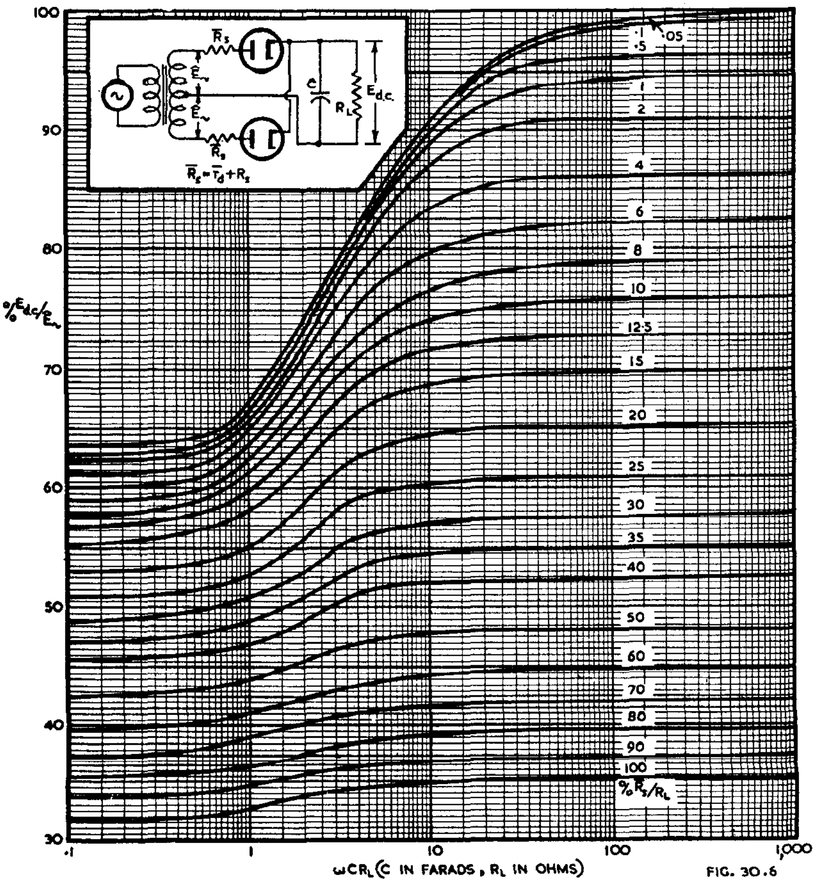


FIG. 30.6

Fig. 30.6. *Ratio of rectified (direct) output voltage to peak a.c. rectifier input voltage, expressed as a percentage, as a function of* ωCR_L *for a full-wave rectifier with a condenser input filter (Ref.* 6).

(iii) To determine peak and average diode currents

This method is for use when complete published data are available such as are usually supplied by the operation characteristics or equivalent published data.

The procedure is illustrated by an example based on type 5Y3-GT as a full wave rectifier under the following conditions :

r.m.s. voltage = $|E_\sim|$ = 350 volts,

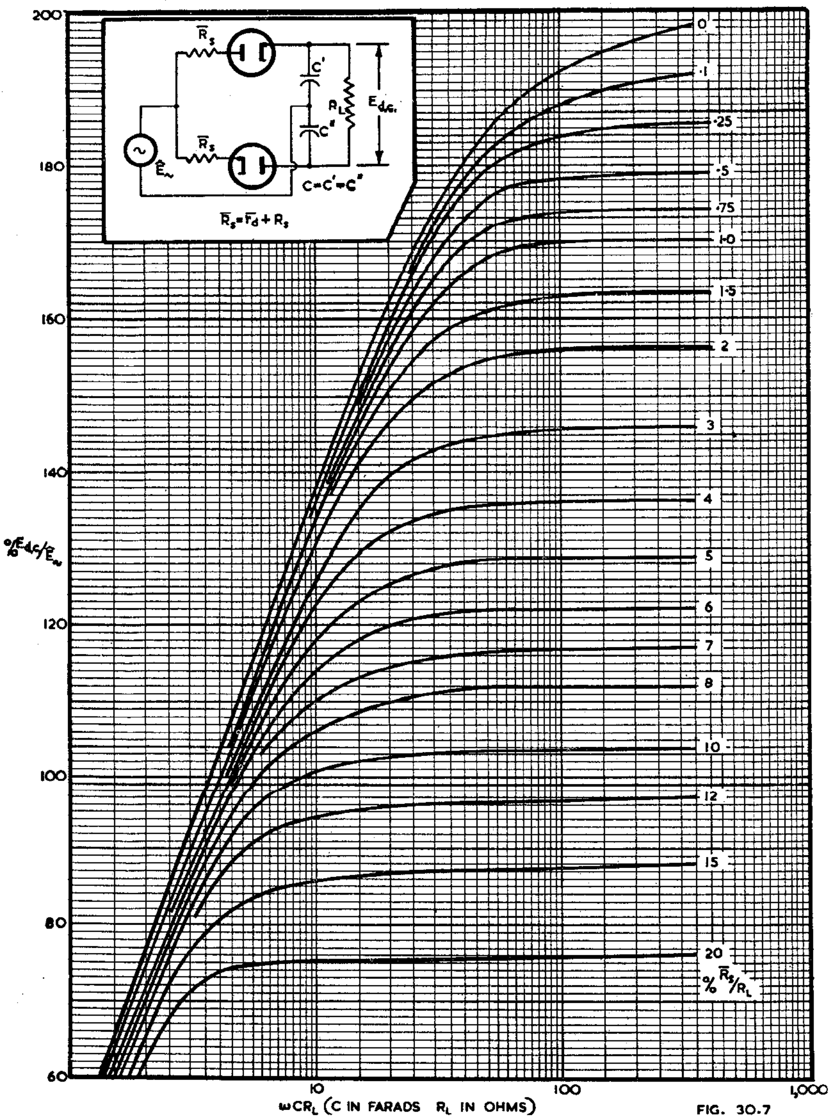


FIG. 30.7

Fig. 30.7. Ratio of rectified (direct) output voltage to peak a.c. rectifier input voltage, expressed as a percentage, as a function of ωCR_L *for a condenser-input voltage doubler (Ref. 6).*

load current = I_L = 125 mA
voltage across load = E_{dc} = 350 volts (from Fig. 30.2A),
load resistance = $R_L = 350/0.125 = 2800$ ohms,
total effective plate supply impedance per plate = R_s = 50 ohms (from Fig. 30.2A),
$C = 10\ \mu$F (from Fig. 30.2A),
f = 60 c/s (from Fig. 30.2A), whence $\omega = 378$.
$\omega CR_L = 378 \times 10 \times 10^{-6} \times 2800 = 10.6$.

Step 1. Determine $\dfrac{E_{dc}}{\hat{E}_\sim}\% = \dfrac{350}{350\sqrt{2}} = 70.7\%$.

Step 2. From Fig. 30.6, knowing $\omega CR_L = 10.6$, we obtain

$$\bar{R}_s/R_L = 13.5\%,$$

whence $\bar{R}_s = 13.5 \times 2800/100 = 378$ ohms.

Step 3. $\bar{r}_d = \bar{R}_s - R_s = 378 - 50 = 328$ ohms.

Step 4. $\hat{r}_d = 0.88\ \bar{r}_d = 0.88 \times 328 = 288$ ohms.

Step 5. $\hat{R}_s = R_s + \hat{r}_d = 50 + 288 = 338$ ohms.

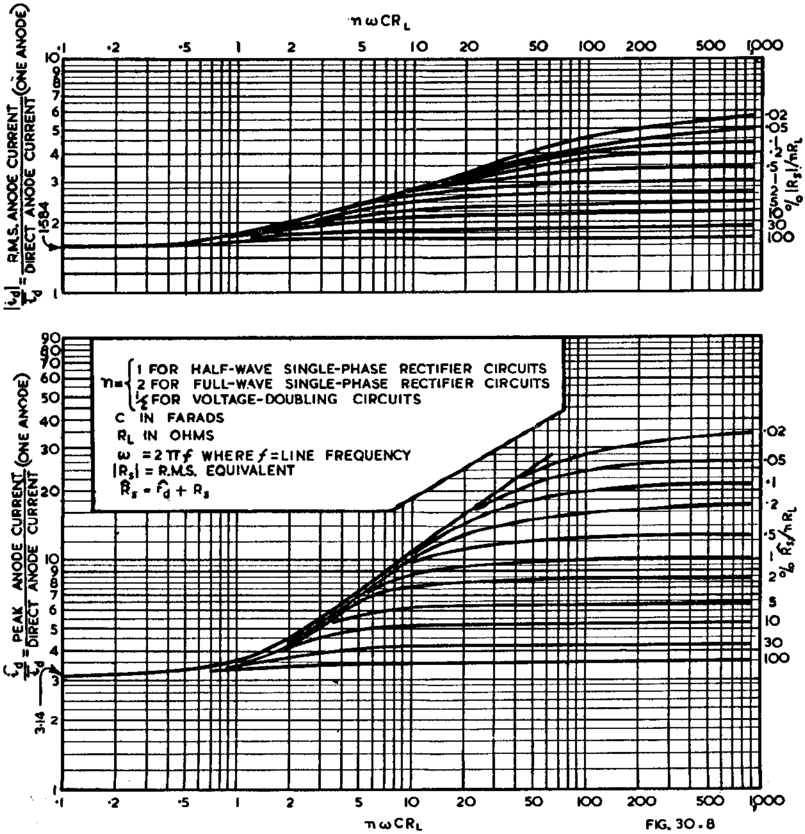


FIG. 30.8

Fig. 30.8 (*above*). *Ratio of r.m.s. diode current to average diode current for one anode, expressed as a function of* ωCR_L ; (*below*) *Ratio of peak diode current to average diode current for one anode, expressed as a function of* ωCR_L (*Ref.* 6).

Step 6. $\frac{\hat{R}_s}{R_L}\% = \frac{338}{2800} \times 100 = 12.1\%$.

Step 7. Knowing that $n = 2$ for full wave rectification,

$$\frac{\hat{R}_s}{nR_L} = \frac{12.1}{2}\% = 6.05\%.$$

Step 8. From Fig. 30.8 (lower) where $n\omega CR_L = 21.2$ we may obtain

$$\frac{\hat{i}_d}{\bar{i}_d} = 6.$$

Step 9. The **average diode current** $\bar{i}_d$:

$\bar{i}_d = I_L$ for half-wave circuits and full-wave voltage doubler circuits,

$\bar{i}_d = \frac{1}{2}I_L$ for full-wave circuits.

In this example $\bar{i}_d = 125/2 = 62.5$ mA.

Step 10. The **peak diode current,** is obtained by substituting the value of $\bar{i}_d$ given by Step 9 in the result of Step 8. In the example

$\hat{i}_d = 6\ \bar{i}_d = 6 \times 62.5 = 375$ mA.

(N.B. the maximum rating is 400 mA).

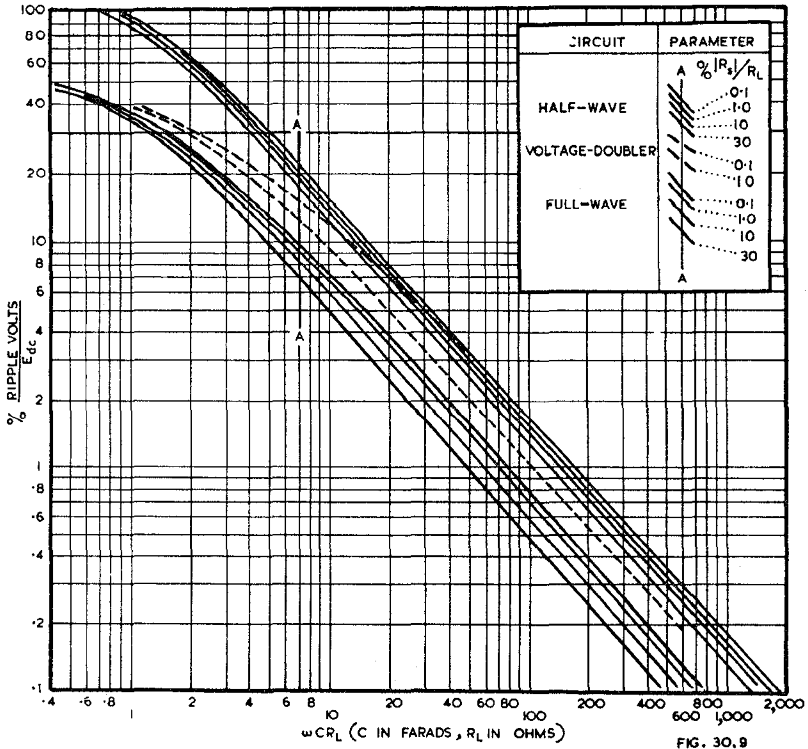


FIG. 30.9

Fig. 30.9. Curves for the determination of the ripple factor of condenser input filter rectifier circuits (Ref. 6).

(iv) To determine ripple percentage

Having determined the peak diode current, we may then proceed to calculate the other unknowns. The same example as in (iii) above is also used here.

Step 1. $|r_d| = \hat{r}_d/0.93 = 288/0.93 = 310$ ohms.
Step 2. $|R_s| = R_s + |r_d| = 50 + 310 = 360$ ohms.
Step 3. $\dfrac{|R_s|}{R_L}\% = \dfrac{360}{2800} \times 100 = 12.8\%$.

Step 4. Applying this value to Fig. 30.9 (note the values shown in the inset, applying to the various curves), and using the value of ωCR_L determined above, the percentage of ripple voltage to direct voltage is given.

In the example, $\dfrac{|R_s|}{R_L} = 12.8\%$ (full wave) and $\omega CR_L = 10.6$ giving

$\dfrac{\text{ripple voltage}}{\text{direct voltage}} = 5.5\%$.

The ripple voltage $|E_R|$ = ripple percentage × direct voltage.

(v) To determine the transformer secondary r.m.s. current $|i_d|$

Knowing the value of $\bar{i}_d$ as determined in (iii) Step 9 above, also the values of n, ωCR_L and $|R_s|/R_L$, Fig. 30.8 (upper curves) will give the value of $|i_d|$.

In the same example $\bar{i}_d = 62.5$ mA ; $n = 2$; $\omega CR_L = 10.6$ and $|R_s|/R_L = 12.8\%$, so that $|i_d|/\bar{i}_d = 2.25$ and $|i_d| = 62.5 \times 2.25 = 140$ mA.

(vi) Procedure when complete published data are not available

Step 1. To determine $\bar{i}_d$.

$\bar{i}_d = I_L$ for half-wave circuits and full-wave voltage doubler circuits,

$\bar{i}_d = \frac{1}{2}I_L$ for full-wave circuits.

Step 2. The diode peak current $\hat{i}_d$ is tentatively assumed to be $6\ \bar{i}_d$. Alternatively, if the output voltage is known, the current ratio may be derived from Fig. 30.10A.

Step 3. From Fig. 30.4, and knowledge of the valve type, the diode peak plate voltage $\hat{e}_d$ corresponding to $\hat{i}_d$ can be found. Therefore $\hat{r}_d = \hat{e}_d/\hat{i}_d$ can be evaluated.

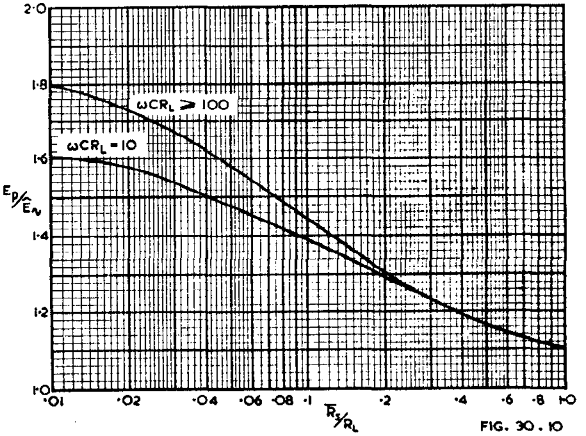


FIG. 30.10

Fig. 30.10. Ratio of operating peak inverse voltage to peak applied a.c. for rectifiers used in condenser input filter circuits.

Step 4. Calculate $\hat{R}_s = \hat{r}_d + R_s$.

Step 5. Using Fig. 30.8 (lower curves), and knowing $n\omega CR_L$, $\hat{R}_s$ and nR_L, determine $\hat{i}_d/\bar{i}_d$. If this differs appreciably from the assumed value, repeat steps 3, 4 and 5.

Step 6. Calculate $|r_d| = \hat{r}_d/0\ 93$.
Step 7. Calculate $|R_s| = R_s + |r_d|$.
Step 8. Calculate the percentage $|R_s|/R_L$ and apply to Fig. 30.9 to determine the ripple percentage.
Step 9. Calculate $|R_s|/nR_L$ and apply to Fig. 30.8 (upper curves) to determine $|i_d|/\bar{i}_d$, and thence $|i_d|$ which is the transformer secondary r.m.s. current.

Step 10. Calculate $\bar{r}_d = \hat{r}_d/0.88$.
Step 11. Calculate $\bar{R}_s = R_s + \bar{r}_d$.

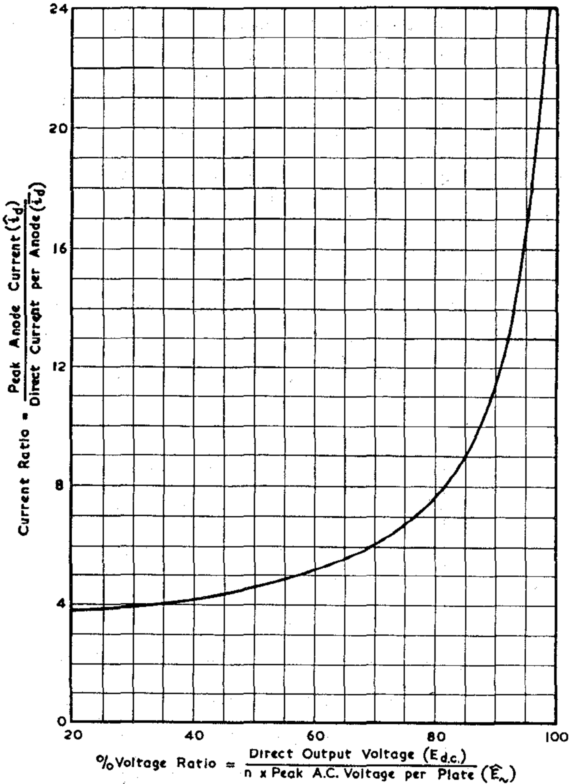


FIG. 30.10A

Fig. 30.10A. *This curve is for full-wave, half-wave and voltage-doubler rectifiers with condenser-input filters. It applies for any size of condenser so long as the condenser is large enough to give maximum output voltage for the given output current and r.m.s. voltage input. For half-wave and voltage-doubler rectifiers the direct current per anode* $\bar{i}_d = I_L$; *for full wave rectifiers* $\bar{i}_d = \frac{1}{2}I_L$.

$n = 1$ *for full-wave and half-wave rectifiers.*
$n = 2$ *for voltage doubler rectifiers.*

Step 12. Calculate the percentage $\bar{R}_s/R_L$.
Step 13. Using Fig. 30.5 for half wave rectification,
or Fig. 30.6 for full wave rectification,
or Fig. 30.7 for voltage doubler circuits,

determine the percentage $E_{dc}/\hat{E}_\sim$.

Step 14. The transformer secondary r.m.s. voltage per plate is given by

$$|E_\sim| = \frac{70.7\ E_{dc}}{\text{percentage } E_{dc}/\hat{E}_\sim}$$

Step 15. The peak inverse voltage under operating conditions is given by Fig. 30.10, but the peak inverse voltage under no-load conditions is equal to $2\hat{E}_\sim$ and the latter must not exceed the valve rating.

Step 16. It is then necessary to confirm that none of the maximum valve ratings has been exceeded.

Example of procedure when complete published data are not available.

Assume type 5Y3-GT as full wave rectifier with $E_{dc} = 350$ volts, $I_L = 125$ mA, $R_s = 50$ ohms, $f = 60$ c/s, $C = 10\ \mu$F. We may derive directly $R_L = 2800$ ohms, $n = 2$, $\omega = 378$, $\omega CR_L = 10.6$.

Step 1. $\bar{i}_d = \frac{1}{2} I_L = 62.5$ mA.

Step 2. Assume $\hat{i}_d = 6\ \bar{i}_d = 375$ mA.

Step 3. From Fig. 30.4, curve 14, $\hat{e}_d = 123$ volts.

Therefore $\hat{r}_d = \hat{e}_d/\hat{i}_d = 123/0.375 = 328$ ohms.

Step 4. $\hat{R}_s = \hat{r}_d + R_s = 328 + 50 = 378$ ohms.
Step 5. Fig. 30.8 (lower curves), where $n\omega CR_L = 21.2$

and $\frac{\hat{R}_s}{nR_L}\% = \frac{378 \times 100}{2 \times 2800} = 6.75\%$,

gives $\hat{i}_d/\bar{i}_d = 5.8$, which differs so slightly from the assumed value of 6 that the calculated values of effective diode resistance may be taken as sufficiently accurate. If the value of $\hat{i}_d/\bar{i}_d$, as calculated above, differed appreciably from the assumed value, it would be necessary to repeat steps 3, 4 and 5.

Peak current $\hat{i}_d = 5.8 \times 62.5 = 362$ mA.

Step 6. $|r_d| = \hat{r}_d/0.93 = 328/0.93 = 352$ ohms.
Step 7. $|R_s| = R_s + |r_d| = 50 + 352 = 402$ ohms.
Step 8. $(|R_s|/R_L) \times 100 = 402 \times 100/2800 = 14.4\%$.
Applying to Fig. 30.9 with $\omega CR_L = 10.6$ gives ripple percentage $= 5.5\%$.
Step 9. $(|R_s|/nR_L) \times 100 = 7.2\%$. Applying this to Fig. 30.8 (upper curves) gives $|i_d|/\bar{i}_d = 2.2$.
Therefore transformer secondary r.m.s. current $= 2.2 \times 62.5 = 138$ mA.

Step 10. $\bar{r}_d = \hat{r}_d/0.88 = 328/0.88 = 373$ ohms.
Step 11. $\bar{R}_s = R_s + \bar{r}_d = 50 + 373 = 423$ ohms.
Step 12. $(\bar{R}_s/R_L) \times 100 = 423 \times 100/2800 = 15.1\%$.

Step 13. Using Fig. 30.6, $E_{dc}/\hat{E}_\sim = 68.8\%$.
Step 14. The transformer secondary r.m.s. voltage per plate is equal to

$$\frac{70.7 \times 350}{68.8} = 360 \text{ volts.}$$

It will be noticed that these values agree within 3% with those determined by the other procedure.

(vii) Approximations when the capacitance is large

Figs. 30.5, 6 and 7 indicate that, when a certain value of ωCR_L has been reached, all curves flatten out. In other words, if we increase the value of the input capacitance C, the output voltage and hence the output current remain constant above a certain value of C. Similarly with the peak current, as indicated by Fig. 30.8.

It is therefore possible to adopt a simplification when the input capacitance is sufficiently large so that any further increase in C does not have much effect on the direct voltage output. Fig. 30.10A enables the ratio of peak to average (direct) currents to be calculated from a knowledge of the voltage ratio and the type of circuit. It may be used as a fair approximation for most typical radio receivers in which $C \geqq 16\ \mu$F for full-wave or $32\ \mu$F for half-wave operation. It should not be used in cases where the circuit impedance is very low, such as a half-wave rectifier in transformerless receivers with no added resistance.

A further approximation, which holds under the same conditions as outlined above, may be used when it is desired to reach the maximum rated direct current per plate and the maximum rated peak current per plate simultaneously, when the latter is six* times the former. Under these conditions

$$\hat{R}_s \approx 0.06\ nR_L$$

where $\hat{R}_s = \hat{r}_d + R_s$
$\hat{r}_d$ = effective peak resistance of diode
R_s = total effective plate supply impedance per plate
n = 1 for half-wave rectification
= 2 for full-wave rectification
and R_L = load resistance.

Also under the same conditions

$$E_{dc} = 0.69 \times \text{peak supply voltage}$$
$$= 0.975 \times \text{r.m.s. supply voltage.}$$

N.B. These relationships are derived from Figs. 30.8 and 30.10A.

(viii) Peak hot-switching transient plate current

The peak hot-switching transient plate current is the current which the diode must carry if the load resistance R_L is short-circuited. This occurs in a practical case when a diode is " hot-switched." The peak hot-switching transient plate current is given by (Ref. 15) :

$$\hat{I}_{max} = \frac{\hat{E}_\sim}{R_s + \hat{r}_{ds}}$$

where $\hat{I}_{max}$ = peak hot-switching transient plate current in amperes
$\hat{E}_\sim$ = peak alternating voltage per plate
R_s = total effective plate supply resistance per plate
and $\hat{r}_{ds}$ = diode resistance when hot-switching current is at its maximum.

The value of $\hat{r}_{ds}$ may be derived from Fig. 30.4, by extending the curves upwards if necessary. If the hot-switching current is greater than 1 ampere, but less than 10 amperes, the resistance may be read from the curves at one tenth of the current value, and the resistance value so derived must then be multiplied by 0.47 (this has an accuracy within about 2% for curves 1 to 17 inclusive). For example, type 5Y3-GT has a rated maximum hot-switching transient plate current of 2.2 amperes per plate. The diode resistance at a plate current of 220 mA is given by Fig. 30.4 curve 14 as 85/0.22 = 386 ohms. The diode resistance $\hat{r}_{ds}$ at a plate current of 2.2 amperes is therefore 386 × 0.47 = 182 ohms. Continuing with the same example, if the peak

---

*This ratio is very commonly used in diode ratings.

alternating voltage per plate is $350\sqrt{2}$, and the peak hot-switching transient current is not to exceed 2.2 amperes, then

$$R_s + \hat{r}_{ds} = 350 \times 1.41/2.2 = 225 \text{ ohms.}$$

$$\text{But} \quad \hat{r}_{ds} = 182 \text{ ohms.}$$

$$\text{Therefore } R_s = 43 \text{ ohms minimum.}$$

(ix) The effect of ripple

The filter condenser C is required to carry a substantial ripple current, the value of which is given approximately by

$|I_R| = |E_R|\omega C$ for half-wave rectification

or $|I_R| = |E_R| 2\omega C$ for full-wave rectification

where $\omega = 2\pi f$

f = supply frequency

$|E_R|$ = ripple voltage r.m.s.

$|I_R|$ = ripple current in amperes r.m.s.

and C is measured in farads.

For example, with a supply frequency of 60 c/s, full-wave rectification and $C = 10\ \mu\text{F}$, a ripple voltage of 20 volts r.m.s. will cause a ripple current of 150 mA. This is the maximum permissible for a dry electrolytic condenser with 450 V working voltage, under JAN-C-62 specification [Chapter 38 Sect. 3(x)]. The maximum permissible ripple currents vary with the capacitance, the working voltage, manufacturer and type. Ripple current ratings of a typical English manufacturer are given on page 194 ; they differ considerably from JAN-C-62.

For any predetermined choice of condenser, temperature voltage and value of R_s/R_L there is a maximum load current which can be drawn from the rectifier without exceeding the ripple current ratings. Based on JAN-C-62, with $(R_s/R_L) = 10\%$ and 60 c/s full wave rectification we have :

Capacitance	350 volt (d.c.) working			450 volt (d.c.) working		
	max ripple current	max. load current	$\frac{\text{load curr.}}{\text{ripple curr.}}$	max. ripple current	max. load current	$\frac{\text{load curr.}}{\text{ripple curr.}}$
10 μF	140 mA	120 mA	86%	150 mA	130 mA	86%
20 μF	180 mA	154 mA	85%	180 mA	150 mA	83%
30 μF	200 mA	168 mA	84%	200 mA	168 mA	84%

Based on English T.C.C. condensers, 450 volt (d.c.) working, ambient temperature 40°C, $(R_s/R_L) = 10\%$ and 50 c/s full wave rectification we have :

Capacitance	Plain foil			Etched foil		
	max. ripple current	max. load current	$\frac{\text{load curr.}}{\text{ripple curr.}}$	max. ripple current	max. load current	$\frac{\text{load curr.}}{\text{ripple curr.}}$
8 μF	—	—	—	67 mA	57 mA	85%
16 μF	260 mA	220 mA	85%	122 mA	103 mA	85%
32 μF	405 mA	344 mA	85%	—	—	—

In the cases listed above, the load current is approximately 85% of the maximum ripple current ; this only applies for $(R_s/R_L) = 10\%$. Values for three conditions are given below :

(R_s/R_L)	1%	10%	30%
$\frac{\text{load current}}{\text{ripple current}}$	73%	85%	102% approx.

In practice, in radio receivers and a-f amplifiers, (R_s/R_L) is usually well within the extreme limits 1% and 30%.

If the ripple current for any desired condition is greater than the permissible limit, the capacitance of a single unit condenser may be decreased and/or the value of R_s may be increased either by selecting a different valve type or adding resistance in series with each plate. Either method of increasing R_s will require a higher transformer voltage. Alternatively two condensers may be connected in parallel, with the total capacitance unchanged, each of which will carry part of the ripple current ; however, equal sharing of current cannot be guaranteed and a large safety margin is desirable. The parallel arrangement confers no appreciable benefits with the T.C.C. ratings, as compared with an increase in capacitance of a single unit.

In general, load currents up to 120 mA may safely be employed with plain foil or 70 mA with etched foil without any investigation.

SECTION 3 : RECTIFICATION WITH CHOKE INPUT FILTER

(i) Rectification with choke input filter (ii) Initial transient current.

(i) Rectification with choke input filter

Where good voltage regulation is required, choke input filters are to be preferred. In this type of circuit, providing the first choke L_1 (Fig. 30.1G) is above a certain critical value L_c, the rectifier valve works under conditions of continuous current current flow and in the ideal case where L_1 is of infinite inductance there would be no fluctuations in this current.

It has been shown (Ref. 6) that L_c should be equal to or greater than

$$\frac{R_s + R_L}{6\pi f} \text{ for full-wave operation} \qquad (1)$$

where R_s = total resistance in series with diode
R_L = load resistance presented to rectified supply
and f = supply frequency.

As an approximation, if R_s is small compared with R_L,

$$L_c \geqq \frac{R_L}{940} \text{ for a 50 c/s supply} \qquad (2)$$

$$\text{and} \quad L_c \geqq \frac{R_L}{1130} \text{ for a 60 c/s supply.} \qquad (3)$$

The above formulae are only stated for full wave rectification as it is not normal practice to use a choke input circuit with a half-wave rectifier owing to the low output voltage which would result.

In applications where the load resistance varies considerably, for example in Class B amplifiers, it is usual to place a bleeder across the supply, thereby reducing the initial value required for L_1. As the required critical value of L_1 decreases with increased load current, the choke can be made with a smaller air gap than necessary for constant inductance at all loads ; the drop in inductance due to d.c. polarization is permissible providing the inductance does not drop below L_c at any load.

This is known as a **swinging choke** ; its design is covered on pages 249 and 250.

The peak diode current is given approximately by

$$\hat{i}_d = I_L + \frac{\hat{E}_\sim \times 0.425}{2\omega L_1 - 1/(2\omega C_1)} \tag{4}$$

or, if $1/(2\omega C_1)$ is very much less than $2\omega L_1$, then

$$\hat{i}_d \approx I_L + \frac{\hat{E}_\sim \times 0.212}{\omega L_1} \,. \tag{5}$$

$$\text{If } L_1 = L_c = R_L/6\pi f, \text{ then } \hat{i}_d \approx 2I_L. \tag{6}$$

$$\text{If } L_1 = 2L_c = R_L/3\pi f, \text{ then } \hat{i}_d \approx 1.5\ I_L. \tag{7}$$

The approximation in equation (4) is due to the neglect of ripple frequencies higher than twice the supply frequency.

If the rectifier valve has a peak current rating equal to or greater than twice the maximum direct load current rating, and if the value of L_1 never falls below L_c, it is not necessary to calculate peak diode currents. The same holds when the peak current rating is equal to or greater than twice the maximum direct current to be drawn from the rectifier. Owing to the desire to limit the rectifier peak current, it is preferable to make the inductance at least $2L_c$ at the highest load current. The drop in inductance at maximum load current will result in a reduction of filtering, but this is not likely to cause any trouble. As the choke will normally be followed by a filter capacitance (C_1 in Fig. 30.1G), any reduction in the inductance of L_1 below L_c at any value of load will cause the rectifier system to take on the characteristics of a condenser input filter and the output voltage will rise.

It is important to remember, when measurements are being made on a filter choke to determine its suitability for use in choke input circuits, that due consideration should be given to the large value of a.c. potential which will exist across it under working conditions. This potential will increase the inductance at low values of d.c. polarization provided that the sum of the a.c. and d.c. fluxes does not cause saturation of the core.

For the accurate calculation of voltage output and regulation of a choke input type filter, the voltage drop due to the resistance of the choke, rectifier and supply must be taken into consideration. The choke resistance can be easily ascertained and the rectifier resistance may be derived from the curves of Fig. 30.4 using the method outlined below. The supply resistance in series with the anode, in a.c. operated equipments, will be equal to the transformer winding resistance [for calculation see pages 99 and 100] plus any added series resistance. In a.c./d.c. equipment it will be equal to the value of the limiting resistor in series with the anode. It is assumed that the rectifier will be operating under conditions of continuous current flow; it can be shown (Ref. 6) that $\hat{r}_d \approx \bar{r}_d \approx |r_d|$ also that the average anode current (one anode) $\bar{i}_d = I_L/2$. The procedure is best illustrated by an example.

Example :—It is desired to design a power supply with choke input filter to deliver 0 to 200 mA at 350 volts using a 5U4-G rectifier at 50 c/s. The choke is assumed to have 100 ohms resistance and the effective supply resistance per anode is 75 ohms. In order to reduce the initial value of L_1, a bleeder to take 20 mA is assumed.

At 20 mA : $R_L = 350/0.02 = 17\,500$ ohms

$L_1 = L_c = 17\,500/940 = 18.6$ H (minimum).

$\bar{i}_d = 20/2 = 10$ mA.

$\hat{i}_d = 2 \times 20 = 40$ mA.

Average anode current during conduction = 20 mA.

Referring to Fig. 30.4 (curve 10) : anode voltage corresponding to 20 mA is 11.7 volts.

$\bar{r}_d = 11.7/0.02 = 585$ ohms.

At 220 mA : $R_L = 350/0.22 = 1590$ ohms.

$L_1 = 2L_c = 2 \times 1590/940 = 3.4$ H (minimum).

$\bar{i}_d = 220/2 = 110$ mA.

$\hat{i}_d = 1.5 \times 220 = 330$ mA.

Average anode current during conduction = 220 mA.

Referring to Fig. 30.4 (curve 10) : anode voltage corresponding to 220 mA is 59 volts.

$\bar{r}_d = 59/0.22 = 268$ ohms.

Voltage drop due to resistance of supply, valve and choke

At 220 mA : = 0.22 (75 + 268 + 100) = 98 volts

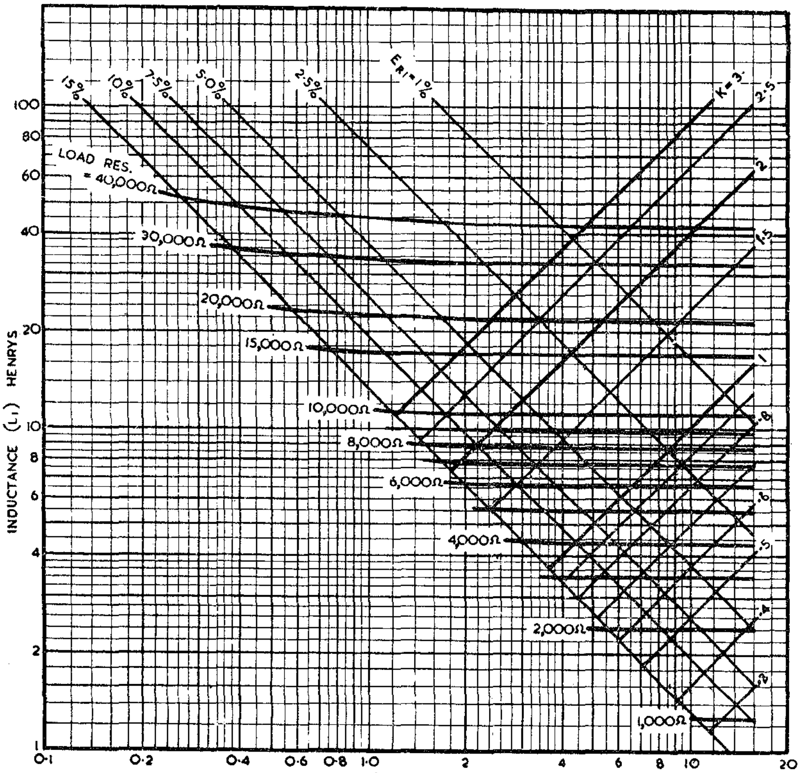


FIG. 30.11

Fig. 30.11. Curves for the determination of the ripple factor of choke input rectifier circuits (based on Ref. 27), applying to the circuit of Fig. 30.1G for full wave rectification on a 50 c/s supply. The curves may be applied to any other supply frequency by multiplying values of inductance and capacitance by 2 for 25 c/s, 1.25 for 40 c/s, or 0.83 for 60 c/s. The ripple curves may be used independently of the K curves and load resistance curves to derive the ripple factor (i.e. ripple voltage E_{R1} expressed as a percentage of the direct load voltage). The operating point at any value of load resistance which occurs in practice should be above (preferably well above) the corresponding load resistance curve, thus determining the inductance L_1. In order to limit the initial (starting) transient current to the maximum peak current rating of the rectifier valve, the operating point should be above and to the left of the corresponding K curve, where

$$K = \frac{\textit{r.m.s. voltage per anode } |E_{\sim}|}{1110 \times \textit{peak plate current rating of diode}}.$$

At 20 mA : = 0.02 (75 + 585 + 100) = 15 volts.

R.M.S. transformer voltage = (350 + 98)/0.9 = 498 volts.

Voltage across load at 20 mA = (498 × 0.9) − 15 = 449 volts.

Value of C_1 : Assume 10% ripple at maximum current, and referring to Fig. 30.11 for $L_1 = 3.4$ H, we obtain $C_1 = 5.7\ \mu$F (8 μF would probably be used).

These results, which show a change of output of 350 to 449 volts when the load is changed from 220 to 20 mA, appear greater than the figures given by the valve curves ; this is because the choke voltage drop has also been taken into consideration.

From the example above it can be seen that the rectifier voltage drop is neither negligible nor constant ; in the case of a 5U4-G it varies from 11.7 volts at 20 mA to 59 volts at 220 mA.

If a lower impedance rectifier such as a 5V4-G had been used, this would have been reduced to 5.4 volts at 20 mA and 27 volts at 220 mA. For practical purposes of calculating the voltage output, a constant value of 16 volts could then be assumed, which would give an error of not more than 3.2%.

Also from the example it can be seen that the effect on output voltage produced by the 75 ohms supply resistance is fairly small, reducing the output by 1.5 volts at 20 mA and 16.5 volts at 220 mA.

When calculations have been completed, a check should be made to see that none of the maximum ratings given in the published data has been exceeded. This will include the value of peak inverse voltage E_p which in a choke input rectifier system will not be greater than $1.65\,\hat{E}_{\sim}$ provided that L_1 does not drop below L_c at any point. If L_1 is lowered below its critical value for any reason, E_p will approach the value for a condenser input rectifier system (see Sect. 2).

(ii) Initial transient current

When initially switching the anode circuit, with the cathode hot, there is a transient current in excess of the steady direct load current. It may be limited to a value equal to the peak anode current rating of the rectifier if the value of the inductance in henrys is equal to, or greater than

$$\left(\frac{|E_{\sim}|}{1110 \times I_{max}}\right)^2 C_1$$

where I_{max} = peak anode current rating of the valve, in amperes
and C_1 = capacitance in microfarads.

This requirement may be met by ensuring that the L_1 and C_1 values applied to Fig. 30.11 meet at a point on or above the corresponding K curve.

SECTION 4 : TRANSFORMER HEATING

For purposes of calculating transformer heating it is necessary to know the equivalent r.m.s. current in the winding supplying the rectifier.

In the case of **condenser input filters** the r.m.s. value of the anode current can be obtained from Fig. 30.8 (upper curves).

For **choke input filters** in which the inductance L_1 is constant, the r.m.s. value of each anode current is given approximately by (Ref. 31)

$$|i_a| = 0.707\left(1 + \frac{\alpha^2}{2}\right)^{\frac{1}{2}} I_L \qquad (1)$$

where $\alpha = \dfrac{R_L}{3\omega L_1} = \dfrac{L_c}{L_1}$.

The following table has been calculated from eqn. (1):

L_1	α	i_a
$= L_c$	1	$0.87\ I_L$
$= 2L_c$	0.5	$0.75\ I_L$
$= 4L_c$	0.25	$0.72\ I_L$
$=$ infinity	0	$0.707\ I_L$

For design purposes it seems reasonable to calculate on the basis of conditions at maximum current. If $L_1 = 2L_c$ at maximum current, as recommended in Sect. 3, the heating current in the transformer may be taken as $0.75\ I_L$.

For further information on transformer heating, see Chapter 5 Sect. 5 pages 236-237.

SECTION 5 : VOLTAGE MULTIPLYING RECTIFIERS

(i) General (ii) Voltage doublers (iii) Voltage tripler (iv) Voltage quadruplers.

(i) General

Where it is required to obtain a higher direct voltage from a given a.c. input than is possible with normal rectifier circuits and where for reasons of weight, economy or other factors it is not desired to use a transformer, voltage multiplying rectifier circuits may be used.

These circuits involve the principle of charging condensers in parallel from the input and adding them in series for the output, the switching being accomplished by the rectifier valves.

(ii) Voltage doublers

The voltage doubler can take one of two forms, half- or full-wave.

Half-Wave. In the half-wave circuit (Fig. 30.12) on one half of the cycle the condenser C_1 is charged through V_1; this voltage is then added in series on the next half cycle to the voltage of the condenser C_2 charged through V_2. A voltage of approximately $2\hat{E}_\sim$ will appear across R_L depending upon the rectifier type, load resistance and values of C_1 and C_2. The ripple frequency, as in all half-wave circuits, will be the same as the supply frequency. C_1 must be rated at the value of $\hat{E}_\sim$ and C_2 at $2\hat{E}_\sim$.

Full-Wave. In this circuit (Fig. 30.13) C_2' and C_2'' are charged on alternate half cycles, approximately $2\hat{E}_\sim$ appearing across the two in series. The ripple frequency will be equal to twice the supply frequency and the condenser ratings should be each equal to $\hat{E}_\sim$.

Comparing the two circuits

The voltage regulation is better for the full wave circuit at low values of ωCR_L and the rating of both condensers need only be $\hat{E}_\sim$ but the circuit suffers the disadvantage of not having a common input and output terminal. The filtering is easier with the full wave circuit as the ripple frequency is twice the supply frequency, the ripple percentages being approximately equal.

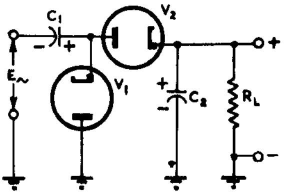


FIG. 30.12

Fig. 30.12. *Half wave voltage doubler rectifier circuit.*

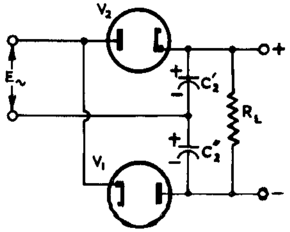


FIG. 30.13

Fig 30.13. *Full wave voltage doubler rectifier circuit.*

In both circuits, the larger the capacitance of the condensers the nearer the output voltage will be to $2\hat{E}_\sim$ and the better the voltage regulation, but care must be taken that the peak current ratings of the rectifiers are not exceeded.

It can be shown (Ref. 10) that at values of ωCR_L greater than 10, the values of $\hat{i}_d/\bar{i}_d$, $E_{dc}/\hat{E}_\sim$, ripple etc. for a half-wave voltage doubler are for all practical purposes the same as the values for the full-wave voltage doubler and calculations of both types can therefore be made by means of the graphs in Sect. 2.

From these graphs it can be seen that if a voltage multiplication of 1.6 or greater is required, the value of ωCR_L should not be less than 100, also that $\bar{R}_s/R_L$ should not be greater than 1.5%. This means that if a voltage doubler is to give a high output and to be of good regulation, the maximum output current is strictly limited.

(iii) Voltage tripler

This circuit (Fig. 30.14) combines in series the outputs of a half-wave doubler and an ordinary half-wave rectifier, giving an output approximately three times $\hat{E}_\sim$. The ripple frequency will be equal to the supply frequency and the condenser ratings will be as for the individual circuits,

i.e. C_1'' rating $= \hat{E}_\sim$; C_2' rating $= \hat{E}_\sim$; C_2'' rating $= 2\hat{E}_\sim$.

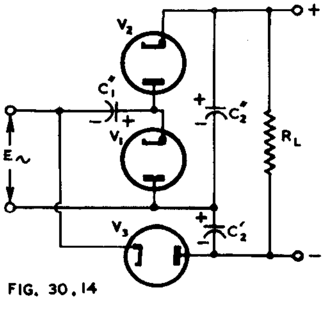


FIG. 30.14

Fig. 30.14. *Voltage tripler rectifier circuit.*

(iv) Voltage quadruplers

There are two suitable circuits as given in Figs. 30.15A and B. (B) is essentially the same as (A) except for the connection of one of the input leads. This alteration results in a supply which has a common input and output lead, the only other alteration being that C_1'' must now withstand $3\hat{E}_\sim$, while C_2' and C_2'' are (as in Fig. 30.12)

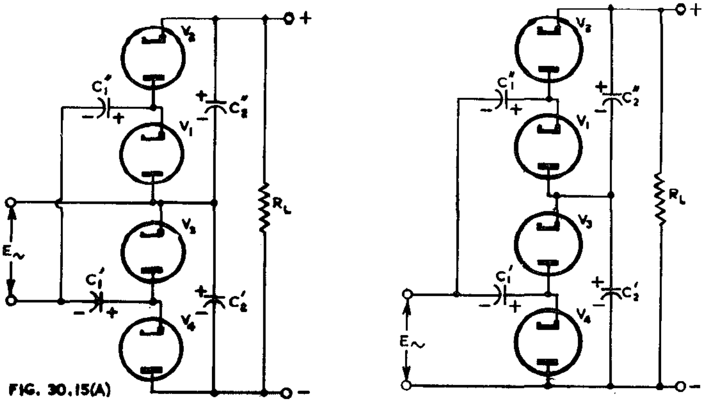


FIG. 30.15(A)

FIG. 30.15(B)

Figs. 30.15(A) *and* (B). *Voltage quadrupler rectifier circuits.*

rated at $2\hat{E}_\sim$ and C_1' at $\hat{E}_\sim$. Another advantage of (B) is that it lends itself to increasing further the number of times the voltage can be multiplied.

For further details on voltage multiplying rectifiers, see References in Sect. 7.

In all cases the polarity of the output can be reversed by reversing the polarity of the rectifiers and condensers.

SECTION 6 : SHUNT DIODE BIAS SUPPLIES

Where a supply of negative bias is required in an amplifier or receiver, as for example the fixed bias operation of an output stage, this can be obtained by the use of a shunt diode without the addition of many components.

If it is desired to make use of a high voltage winding on the power transformer for negative bias, the voltage so obtained is generally much greater than is required

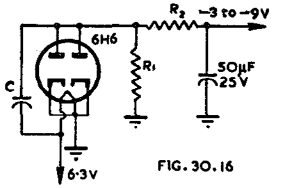


FIG. 30.16

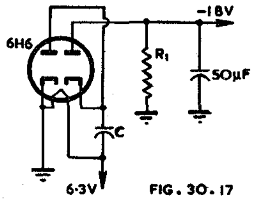


FIG. 30.17

Fig. 30.16. *Shunt diode bias supply suitable for the bias of r-f ; i-f ana a-f amplifier valves.*

Fig. 30.17. *Voltage doubler bias supply suitable for the bias of output stages.*

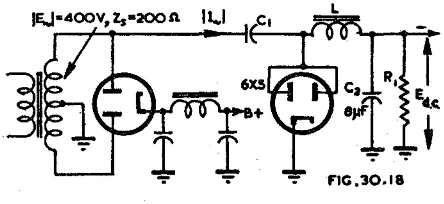


FIG.30.18

Fig. 30.18. *Shunt diode bias supply fed from the transformer winding supplying the main rectifiers.*

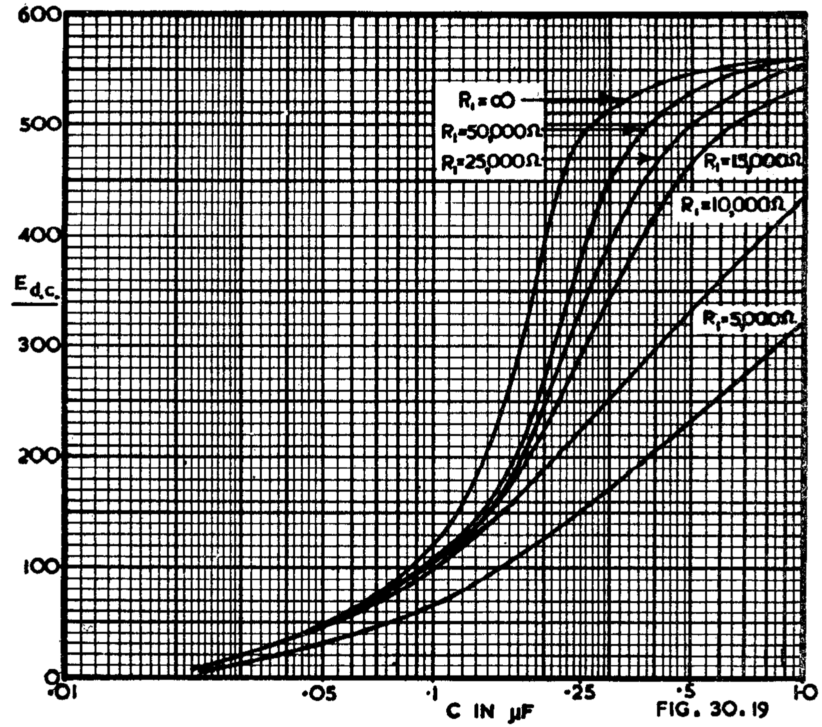


FIG. 30.19

Fig. 30.19. *Output voltage of the circuit of Fig.* 30.18 *for various values of* C_1 *and* R_1.

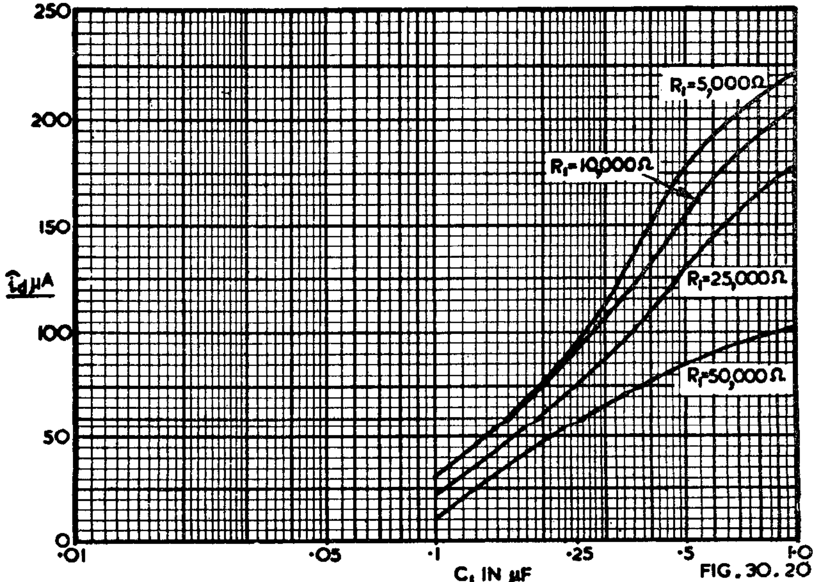


FIG. 30. 20

Fig. 30.20. *Rectifier peak current values for the circuit of Fig.* 30.18 *for various values of* C_1 *and* R_1.

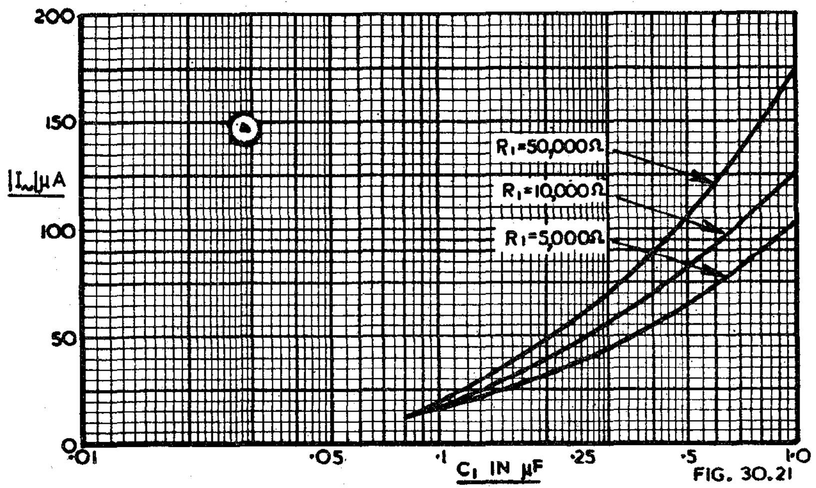


FIG. 30.21

Fig. 30.21. *R.M.S. transformer secondary current in the winding supplying the shunt diode circuit of Fig.* 30.18 *for various values of* C_1 *and* R_1.

for bias. In such a case power would be wasted in voltage dividers. The shunt diode system allows the use of a 6H6 type rectifier since the cathode is at earth potential. It is often possible to use a spare diode in one of the valves already in the equipment, thus doing away with the need for an extra valve.

Two versions of the circuit are shown in Figs. 30.16 and 30.17, Fig. 30.16 being suitable for the bias on r-f, i-f and a-f voltage amplifier valves. Fig. 30.17 is a voltage doubling circuit useful for the bias voltage of output stages. It has a maximum output voltage of 18 volts when supplied from a 6.3 volt heater line.

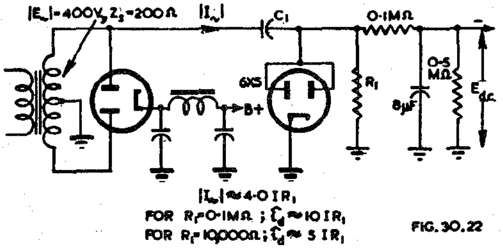


FIG. 30.22

Fig. 30.22. *Shunt diode bias supply with r.c. filtering.*

When more than 18 volts are required the condenser C_1 may be fed from the transformer winding supplying the main rectifier in the equipment. This is shown in Fig. 30.18 and typical values are given together with the measured performance (Figs. 30.19-21) in order that the magnitude of the various quantities may be assessed. The irregularities in the curves of output voltage for various values of C_1 are due to the resonance of C_1 and L, but apart from modifying the shape of rectifier current pulses no other undesirable effects are evident. Care must be taken that the filter condenser C_2 is isolated from C_1 by a high value of impedance or large currents will be drawn from the transformer windings. In cases where only low output currents are required, L may be replaced by a resistor of not less than 100 000 ohms. This circuit arrangement is shown in Fig. 30.22, the output voltage for various values of capacitance being given in Fig. 30.23.

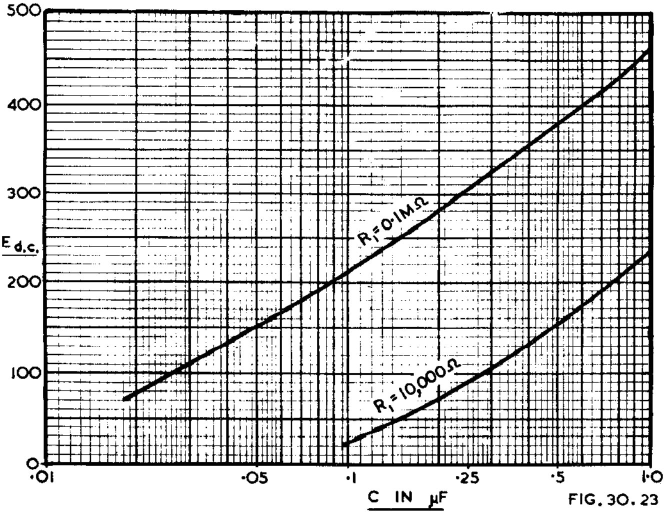


FIG. 30.23

Fig. 30.23. *Output voltage of the circuit of Fig.* 30.22 *for various values of* C_1 *and* R_1.

SECTION 7 : REFERENCES

1. Cockcroft, J. D., and E. T. S. Walton, Proc. Roy. Soc. (London) 136.619 (1932).
2. Dellenbauch, F. S., Jr., and R. S. Quimby, " The important first choke in high voltage rectifier circuits," Q.S.T. 16.2 (Feb. 32) 15.
3. Dellenbauch, S. F., Jr., and R. S. Quimby " The first filter choke—its effect on regulation and smoothing," Q.S.T. 16.3 (March 1932) 26.
4. Dellenbauch, F. S. Jr., and R. S. Quimby, " The economical design of smoothing filters," Q.S.T. 16.4 (April 1932) 33.
5. Reich, H. J. (book) " Theory and Applications of Electron Tubes " (McGraw-Hill, 2nd Edit. 1944) 564.
6. Schade, O. H. " Analysis of rectifier operation," Proc. I.R.E. 31.7 (July 1943) 341.
7. Waidelich, D. L. " Voltage multiplier circuits," Elect. 14.5 (May 1941) 28.
8. Waidelich, D. L. " Full-wave voltage doubling rectifier circuit " Proc. I.R.E. 29.10 (Oct. 1941) 554.
9. Waidelich, D. L., and C. H. Gleason " The half-wave voltage doubling rectifier circuit " Proc. I.R.E. 30.12 (Dec. 1942) 535.
10. Waidelich, D. L., and C. L. Shackelford, " Characteristics of voltage multiplying rectifiers " Proc. I.R.E. 32.8 (Aug. 1944) 470.
11. Waidelich, D. L., and H. A. K. Taskin " Analysis of the voltage tripling and quadrupling rectifier circuits," Proc. I.R.E. 33.7 (July 1945) 449.
12. " Use of the shunt diode for supplying bias voltage " Elect. 18.9 (Sept. 1945) 218.
13. Chadwick, E. W. " Voltage multiplier circuits with selenium rectifiers " Comm. 27.1 (Jan. 1947) 14.
14. " Selenium rectifiers in home receivers " Tele-Tech 6.1 (Jan. 1947) 73.
15. Kauzmann, A. P. " Determination of current and dissipation values for high-vacuum rectifier tubes " R.C.A. Rev. 8.1 (March 1947) 82.
16. Waidelich, D. L. " Analysis of full-wave rectifier and capacitive-input filter " Elect. 20.9 (Sept. 1947) 120.
17. Berkman, R. " Using selenium rectifiers " Q.S.T. 31.10 (Oct. 1947) 50.
18. Tucker, D. G. " Rectifier resistance laws " W.E. 25.295 (April 1948) 117.
19. Rowe, E. G., R. E. B. Wyke and W. Macrae " Power diodes " Part 1 " The design of high-vacuum oxide-coated rectifiers " Electronic Eng. 20.245 (July 1948) 214.
20. Dishington, R. H. " Diode circuit analysis " E.E. 67.11 (Nov. 1948) 1043.
21. " The copper oxide rectifier " E.E. 67.11 (Nov. 1948) 1051.
22. Ramsay, H. T. " The rating of small- and medium-power thermionic rectifiers " Jour. I.E.E. 94. Part III 30 (July 1947) 260.
23. Clarke, C. A. " Selenium rectifier characteristics " Elect. Comm. 20.1 (1941) 47.
24. Yarmack, J. E. " Selenium rectifiers and their design " Trans. A.I.E.E. 61 (July 1942) 488.
25. " Selenium rectifiers for closely regulated voltages " Elect. Comm. 20.2 (1941) 124.
26. Richards, E. A. " The characteristics and applications of the selenium rectifier " Jour. I.E.E. 88 Part III (Dec. 1941) 238 ; 89 Part III (March 1942) 73.
27. " Air Cooled Transmitting Tubes " Technical Manual TT3, Radio Corporation of America (1938).
28. Terman, F. E. (book) " Radio Engineers' Handbook " (McGraw-Hill Book Company, 1st Edit. 1943) p. 601.
29. Lee, R. " Choke-input filter chart " Elect. (Sept. 1949) 112.
30. Lee, R. " Additional uses for rectifier filter chart " Elect. 22.9 (Sept. 1949) 174.
31. Builder, G. " A note on full wave rectifiers " (unpublished paper).
32. Dunham, C. R. " Some considerations in the design of hot-cathode mercury-vapour rectifier circuits " 75.453 (Sept. 1934) 278.

Additional references will be found in the Supplement commencing on page 1475.