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Capacitor Input Filter Design With Silicon Rectifier Diodes

by

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Diode resistance is a non-linear quantity. Unlike high-vacuum tube rectifier circuits the contribution of the diode to total charging resistance R is negligible in most cases. Only where very close regulation is required in low voltage circuits (say below 12 volts) might it be a factor. In any case the forward E-I characteristic on the specification sheet of the diode used can be utilized for obtaining equivalent resistance values for peak or average when required. For all practical cases in filter design work for conventional power supplies equivalent semiconductor diode resistance may be neglected.

REGULATION

The larger the filter-load time constant is made with respect to the period T of the input voltage waveform the smaller will be the deviation of the average load voltage E_{dc} from its no-load value E_m. Conversely, if the filter-load time constant is reduced by, for example, an increase in load (R_L becomes smaller) the average output voltage E_{dc} is reduced from its no-load value. Thus the average, or DC, output voltage with a capacitor input filter will vary widely with variations in load. The power supply is then said to have large, i. e. poor, load voltage regulation. Figures 6, 7, and 8 **are empirical curves which show these relationships of E_{dc}/E_m as a function of filter-load time constant R_L C, circular supply frequency ω, and R/R_L for various commonly used circuits.**

RIPPLE

The ripple content in the output of the filter is a good measure for the quality of the output voltage relative to a pure direct voltage. It is defined as the ratio of the RMS value of the AC components of the output voltage (as measured with a capacitively coupled VTVM) to the direct, or DC, value (as measured with a DC meter) expressed on a per cent basis. Figure 4 shows per cent ripple voltage as a function of filter-load time constant, supply frequency, and charging resistance.

The ripple content in the output, like load voltage regulation, is very sensitive to the magnitude of the load. As, for example, the load is increased (R_L is reduced) the peak-to-peak swing of the instantaneous load voltage waveform is increased because, at the end of the discharge interval illustrated in Figure 1b, the capacitor will have discharged to a lower voltage due to the shorter discharge time constant R_L C.

The job required of the smoothing filter for a given per cent output ripple is, of course, very dependent on the inherent ripple of the raw rectified waveform at the input to the filter. As the period T of the input waveform is reduced the duration of the discharge interval is decreased. For a given load-filter time constant the capacitor, therefore, discharges less for a higher input frequency. Not only has the load voltage regulation of the circuit improved in this case but the peak-to-peak excursion of the load voltage, and hence the ripple, is reduced.

For example, the unfiltered half-wave circuit input used in the illustration of Figure 1 has a theoretical ripple of 121%. It thus has more "AC" in the output than "DC". By going to a full wave circuit the inherent circuit output ripple is reduced by over 50%. Changing the input to three phase full-wave reduces the inherent circuit ripple to about 4%. For a hypothetical 10 ohm load it would require over 10,000 microfarads of capacity to achieve this 4% ripple with a half-wave circuit!

COMMON CAPACITOR INPUT FILTER CIRCUITS AND DESIGN CHARTS

Figures 2 and 3 show some commonly used single phase capacitor input filter circuits. Design charts, Figure 5 through 8 apply to these circuits.

The half-wave circuit offers the ultimate in simplicity. However, it has a higher inherent output ripple and greater voltage regulation. The full-wave circuits offer less ripple and better regulation at the expense of more components. For a given DC output voltage and current the bridge circuit allows the use of lower rated PRV rectifier diodes than the center-tap; the center-tap, conversely, allows the use of only half the number of diodes although at twice the PRV rating of that in the bridge circuit.

The design charts for the voltage doubler apply to both half-wave and full-wave circuits for values of $\omega CR_L > 10$. It is not usual to operate doubler circuits below this value if any amount of voltage multiplication is to be achieved.

The main advantage of the half-wave doubler is that it has a common input and output terminal. However, one capacitor (C2) must be rated for twice the peak of the AC supply line.

The capacitors in the full-wave doubler circuit need be rated for only the peak of the AC supply. The full-wave circuit also has superior voltage regulation for lower values of ωCR_L that might be reached for a high load excursion (low R_L).

DESIGN PROCEDURE

The following design procedure may be followed where the output is given and the components and input are to be determined. When both input and output are specified some steps may be interchanged as suggested in Example II.

Known:

1. Desired DC output voltage E_{dc}
2. Desired DC output current I_{dc}
3. Load Resistance $R_L = \frac{E_{dc}}{I_{dc}}$
4. Maximum permissible ripple in per cent
5. Supply circular frequency $\omega = 2\pi f$
6. Resistance of filter capacitor charging circuit R (usually resistance of transformer secondary)

1) Determine value of filter capacitor C for maximum permissible ripple in per cent and for R/R_L from Figure 4.

Use the ratio R/R_L for the initially known value of R. If R is unknown make an assumption. If additional surge resistance R_s must be added later this step can be rechecked.

2) Select proper rectifier diode from specification sheet:

- a) If ratings are given in terms of average diode current versus temperature with peak-to-average current ratio as a parameter (example Figure 10), determine peak-to-average current in circuit experimentally or enter Figure 5 with $n\omega CR_L$ to find $I_{FM}/I_{F(AV)}$.
- b) If ratings are given in terms of average current versus temperature derating required as a function of conduction angle, determine conduction angle α experimentally or by entering Figure 11 with ωCR_L.

3) Determine required AC input voltage E_{ac} for values of ωCR_L and R/R_L from Figure 6 - half-wave circuit; Figure 7 - full-wave circuits; Figure 8 - doubler circuits.

4) Determine value of additional surge resistance R_s. Use diode specification sheet to find rated I^2t of diode being considered.

- a) Evaluate following expression:

$$\frac{CE_m}{\sqrt{3 I^2 t}}$$, in which

C = Input capacitance corrected for maximum commercial tolerance (usually 200% of nominal value)

E_m = Peak value of supply voltage corrected for 10% high line condition (1.1 x nominal value)

I^2t = I^2t rating obtained from spec bulletin for rectifier previously selected (ampere^{2}seconds.)

- b) Determine RC by entering Figure 9.
- c) Determine total series surge resistance, R, required by dividing value of RC found in step (b) by value of capacitance, C, determined earlier.

  Any resistance already in the circuit (line, transformer, etc.) may be deducted in order to obtain the value of lumped surge resistance, R_s, that must be added.

5) Recheck ripple and E_{dc}/E_m for new value of R/R_L.

EXAMPLES

I Full Wave Bridge Circuit (see Figure 2b)

$$\left.\begin{array}{l} \text{Desired } E_{dc} = 100 \text{ volts DC} \\ \text{Desired } I_{dc} = 500 \text{ ma} \end{array}\right\} \text{ or } R_L = \frac{100}{.5} = 200 \text{ Ohms}$$

Ripple not to exceed 10%

Supply line frequency = 60 cps

Design Procedure:

We assume a total charging resistance of $R = 4$ ohms, or $R/R_L = \frac{4}{200} = 2\%$.

1. For $r \leq 10\%$, from Figure 4, $\omega C R_L \geq 6$, or

   $C \geq \frac{6}{\omega R_L} = \frac{6}{(377)(200)} = 80$ MFD, say 100 MFD.

2. For $n\, \omega C R_L = 2\,(377)\,100\,(10^{-6})\,200 = 15$, from Figure 5, $\frac{I_{FM}}{I_{F\,(AV)}} = 8$

3. **Considering a diode having the rating shown in Figure 10 shows that for the above peak-to-average current ratio each diode can carry about 1.1 amp average at $T_A = 50^{\circ}$. It is apparent that the diode is not limiting the output rating.**

4. For $\omega C R_L = 7.5$ and the assumed $R/R_L = 2\%$, from Figure 7, $\frac{E_{dc}}{E_m} = 85\%$,

   or $E_m = \frac{E_{dc}}{.85} = \frac{100}{.85} = 117$ volts.

   Therefore, $E_{ac} = \frac{E_m}{\sqrt{2}} = \frac{117}{\sqrt{2}} = 83$ volts AC.

5. Checking the total charging resistance required we find from the specification bulletin that the 4JA10 has a rated $I^2t = 5$ amp^{2}seconds.

   $$\frac{C\,E_m}{\sqrt{3\,I^2t}} = \frac{2\,(100)\,10^{-6}\,(1.1)\,117}{\sqrt{15}} = .0067$$

   From Figure 9, $RC = 3 \cdot 10^{-4}$, or $\underline{R} = \frac{3 \cdot 10^{-4}}{100 \cdot 10^{-6}} = \underline{3 \text{ Ohms}}$

   It is very likely that in the selection of the required transformer the greatest part if not all of this resistance will appear in the secondary winding. The need for adding very little if any external surge resistance R_s is the benefit of having selected a diode with a relatively large value of I^2t even though, in this example, it is "loafing" from the point of view of average current.

6. Rechecking ripple and $\frac{E_{dc}}{E_m}$ for $\omega C R_L = 7.5$ and $R/R_L = \frac{3}{200} = 1.5\%$:

   From Figure 7: $\frac{E_{dc}}{E_m} = 87\%$, or $E_{ac} = \frac{E_{dc}}{(.87)\sqrt{2}} = 81.5$ volts, say $E_{ac} = 82$ volts

   From Figure 4: Ripple = 9%. This is below the maximum allowable ripple specified.

Experimental Verification

The circuit of Figure 2b was set up with:

E_{ac} = 82 volts

C = 104.5 MFD (measured)

R = 3 Ohms

R_L = 200 Ohms

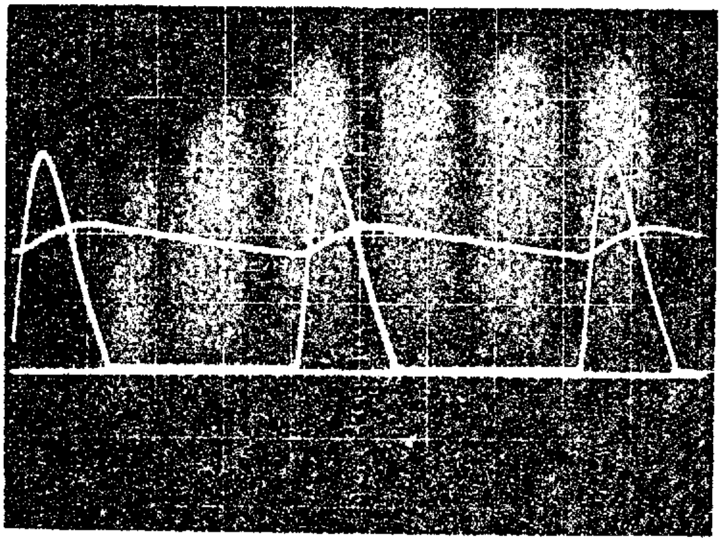
Measured values were as follows:

$E_{dc} = 100$ volts

Ripple $= 6.9\ V_{rms}$ or $\frac{6.9}{100} = 6.9\%$

It is seen that within measurement accuracies the desired E_{dc} was achieved and that the ripple measured was better by $\frac{2.1}{9} \approx 23\%$. If measured component values are used E_{dc} falls within a few per cent and ripple to about 10% of calculated.

Figure 11 shows an oscillogram of output voltage E_{dc} and capacitor charging current in the circuit of the above example.



Voltage: 50 V/div.

Current: 900 ma/div.

H: 2 msec/div.

FIGURE 11

Oscillogram of Output Voltage and Capacitor Charging Current In Full-Wave Capacitor Input Filter Circuit ($\omega C R_L = 7.8$)

II. Half-Wave Doubler Circuit (see Figure 3a)

Desired $E_{dc} = 265$ volts DC
Desired $I_{dc} = 500$ ma
$\Big\}$ or $R_L = \frac{265}{.5} = 530$
Ripple not to exceed 5%
Supply line voltage $E_{ac} = 117$ volts AC
Supply line frequency = 60 cps

Design Procedure

As in the previous example, a starting assumption must be made regarding charging resistance R. Since this doubler is to operate directly from the AC supply line we will not be able to depend on any transformer secondary resistance. A minimum assumption for R may be $R = R_s = 2$ Ohms.

Also, since in this example both output and input voltage are given, it will be convenient to change the order of the steps in the design procedure to first determine the minimum value of $\omega C R_L$ required to give the desired voltage relationship $\frac{E_{dc}}{E_m}$. Ripple will then be checked later.

1. With $E_m = \sqrt{2}\, E_{ac} = \sqrt{2}\,(117) = 165$, or $\frac{E_{dc}}{E_m} = \frac{265}{165} = 160\%$ and

$R/R_L = \frac{2}{530} \approx .4\%$, from Figure 8, $\omega C R_L \simeq 20$, or $C = \frac{20}{\omega R_L}$

$\underline{C} = \frac{20}{(377)(530)} = \underline{100 \text{ MFD}}$

2. For $n \omega C R_L = 10$ and $R/R_L = .4\%$ from Figure 5, $\frac{I_{FM}}{I_{F(AV)}} = 10$

3. Considering again the type diode shown in Figure 10 we see that the diode under this condition is capable of 1.0 amp average per cell output at $T_A = 50^\circ C$. The diode will thus be applied well within its continuous rating.

4. Having selected the diode the minimum allowable charging resistance R may now be determined based on the diode's I^2t rating. ($I^2t = 5$ for the diode used in this example).

   Evaluating

   $$\frac{C\, E_m}{\sqrt{3\, I^2 t}} = \frac{(2)\, 100\, (10^{-6})\, 165\, (1.1)}{\sqrt{15}} = .0094$$

   From Figure 9, $RC = 4 \cdot 10^{-4}$, or $R = \frac{4 \cdot 10^{-4}}{100 \cdot 10^{-6}} = \underline{4 \text{ Ohms}}$

   Our initial assumption was low and we must therefore recheck voltage and determine ripple with the new value of $R/R_L = \frac{4}{530} = .76\%$

5. From Figure 8 for $\omega C R_L = 20$, and $R/R_L = .76\%$, $\frac{E_{dc}}{E_m} = 158\%$ or $E_{dc} = 1.58 \sqrt{2}\,(117) = 260$ volts DC.

   This is within less than 2% of the design value.

6. Ripple can now be determined from Figure 4 for $\omega C R_L = 20$ and $R/R_L = .75\%$. We see that ripple $\approx 6\%$. This is within the accuracy of the method, measurements, and components.

Experimental Verification

The circuit of Figure 3a was set up with

E_{ac} = 118 volts AC
C_1 = 94.5 MFD; C_2 = 104.6 MFD (measured)
R = 4 Ohms
R_L = 530 Ohms

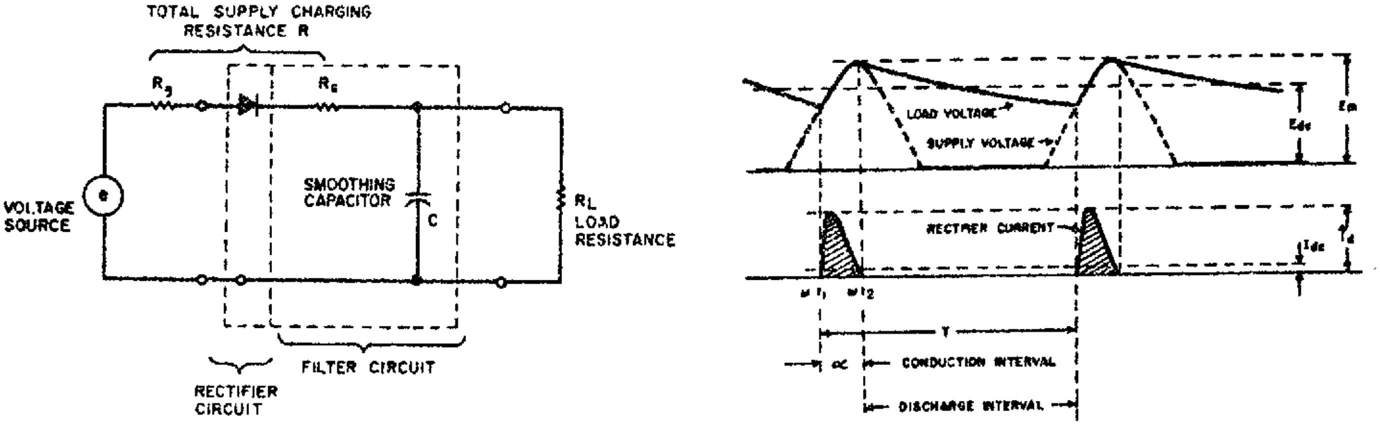
Measured values were as follows:

E_{dc} = 245 volts DC
Ripple = 13.9 volts RMS or $\frac{13.9}{245} \approx 5.7\%$

It is seen that within the component tolerance (in the area of 5% in this example) and measurement accuracies (approximately 2%) the design voltage was achieved to within $\frac{265 - 245}{265} = 7.5\%$; the ripple was $\frac{5.7 - 5.0}{5.0} = 14\%$ of design value or $\frac{5.7 - 5.5}{5.5} = 3.7\%$ of calculated value. In a given production design component tolerance analysis would be coordinated with allowable voltage and ripple tolerances to yield appropriate component specifications.

REFERENCE

1. Analysis of Rectifier Operation, O. H. Schade, Proceedings IRE, Vol. 31, No. 7, July 1943, pp 341-361.

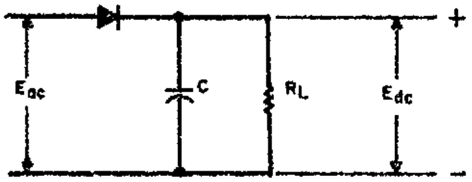


(a) BASIC CAPACITOR INPUT FILTER RECTIFIER CIRCUIT

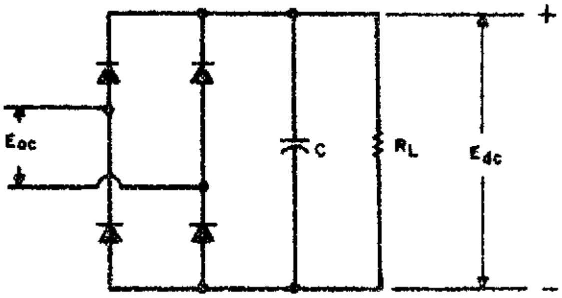
(b) VOLTAGE AND CURRENT RELATIONSHIPS

FIGURE 1

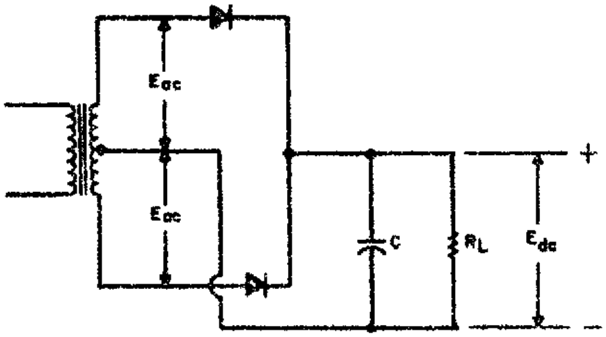
Typical Circuit and Voltage-Current Relationships for Capacitor Input Filter Circuit



(a) HALF-WAVE CIRCUIT



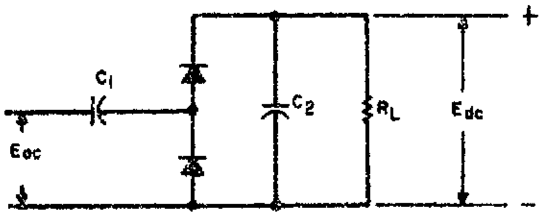
(b) FULL-WAVE BRIDGE CIRCUIT



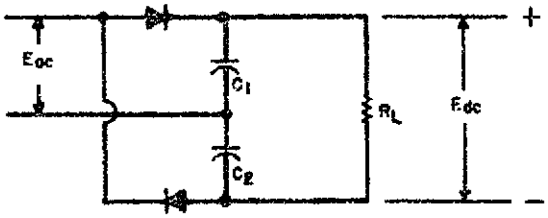
(c) FULL-WAVE CENTER-TAP CIRCUIT

FIGURE 2

Common Capacitor Input Filter Circuits



(a) HALF-WAVE DOUBLER CIRCUIT



(b) FULL-WAVE DOUBLER CIRCUIT

FIGURE 3

Common Voltage Doubling Circuits

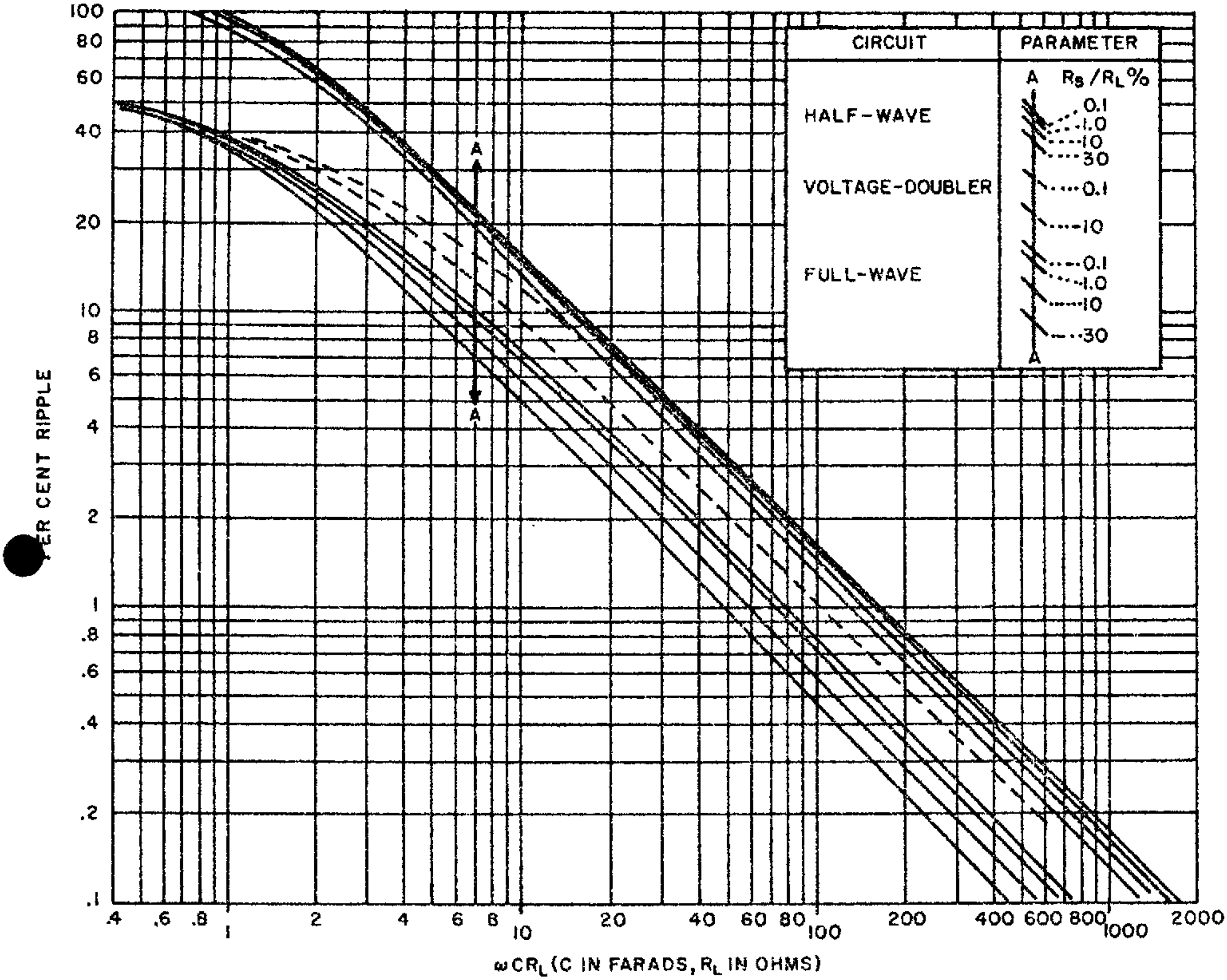


FIGURE 4

Per Cent Ripple of Capacitor Input Filter Circuits

(From O. H. Schade, Proceedings IRE, 1943, by permission)

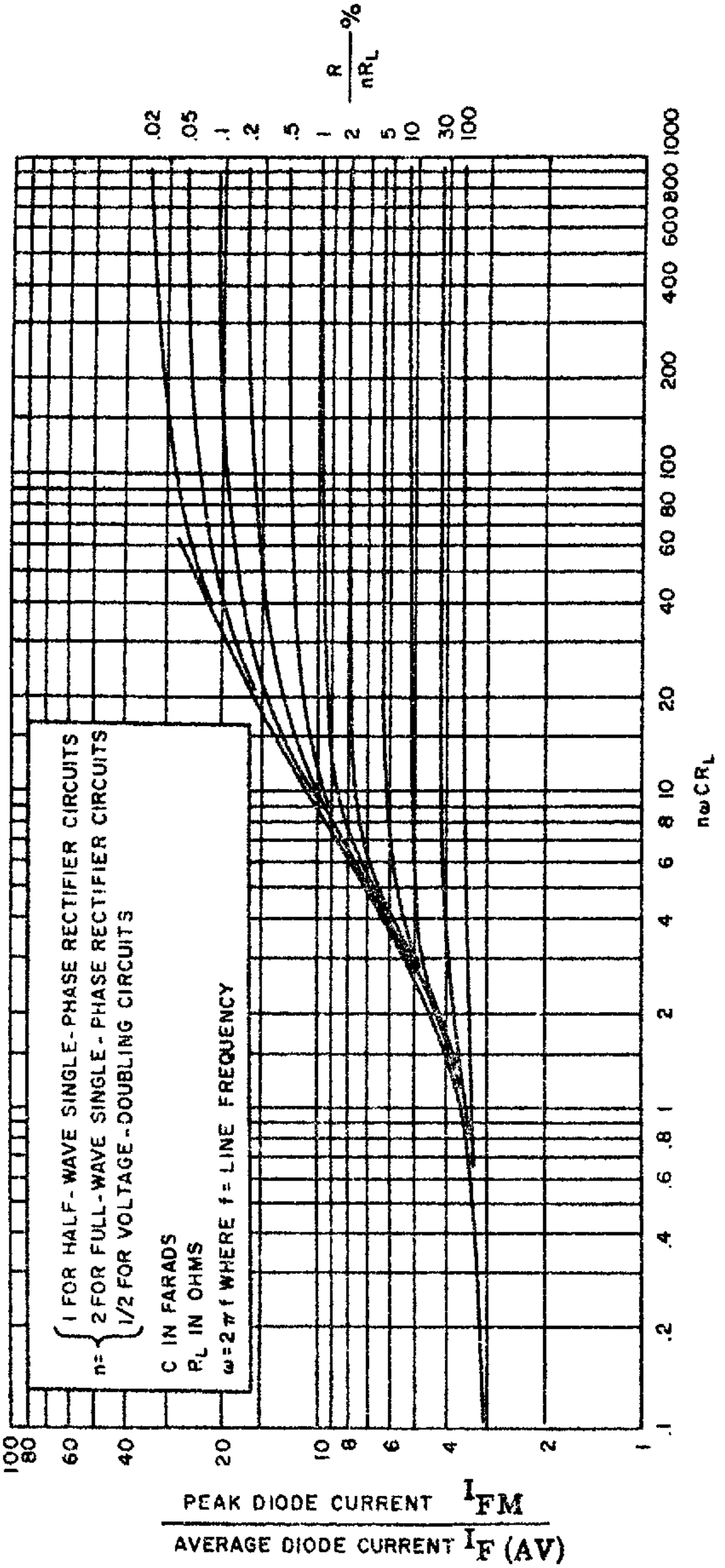


FIGURE 5

Peak-to-Average Ratio of Rectifier Diode Current in Capacitor Input Filter Circuits
(From O. H. Schade, Proceedings IRE, July, 1943, by permission)

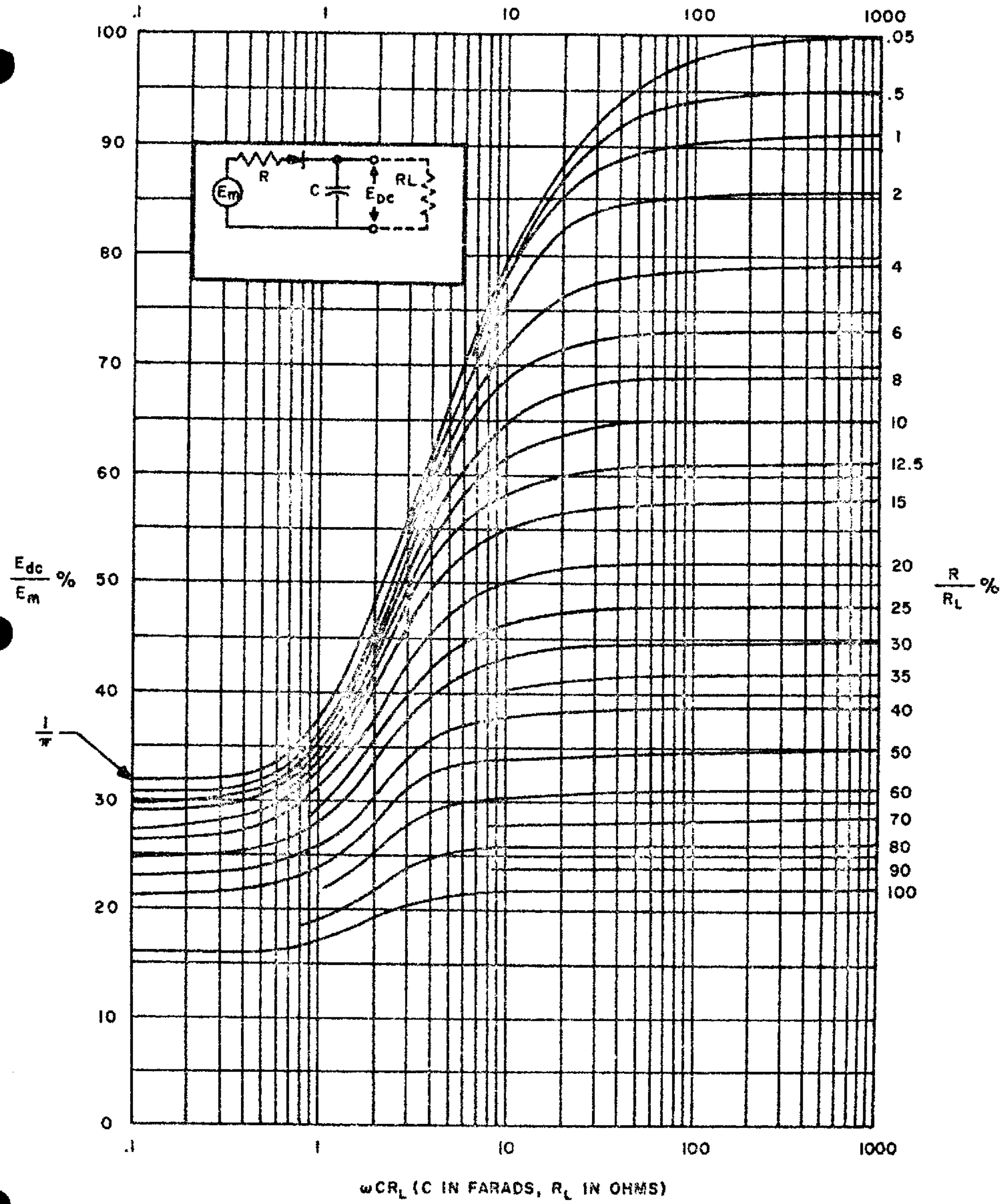


FIGURE 6

Voltage Ratio For Half-Wave Capacitor Input Filter Circuit
(From O. H. Schade, Proceedings IRE, July, 1943, by permission)

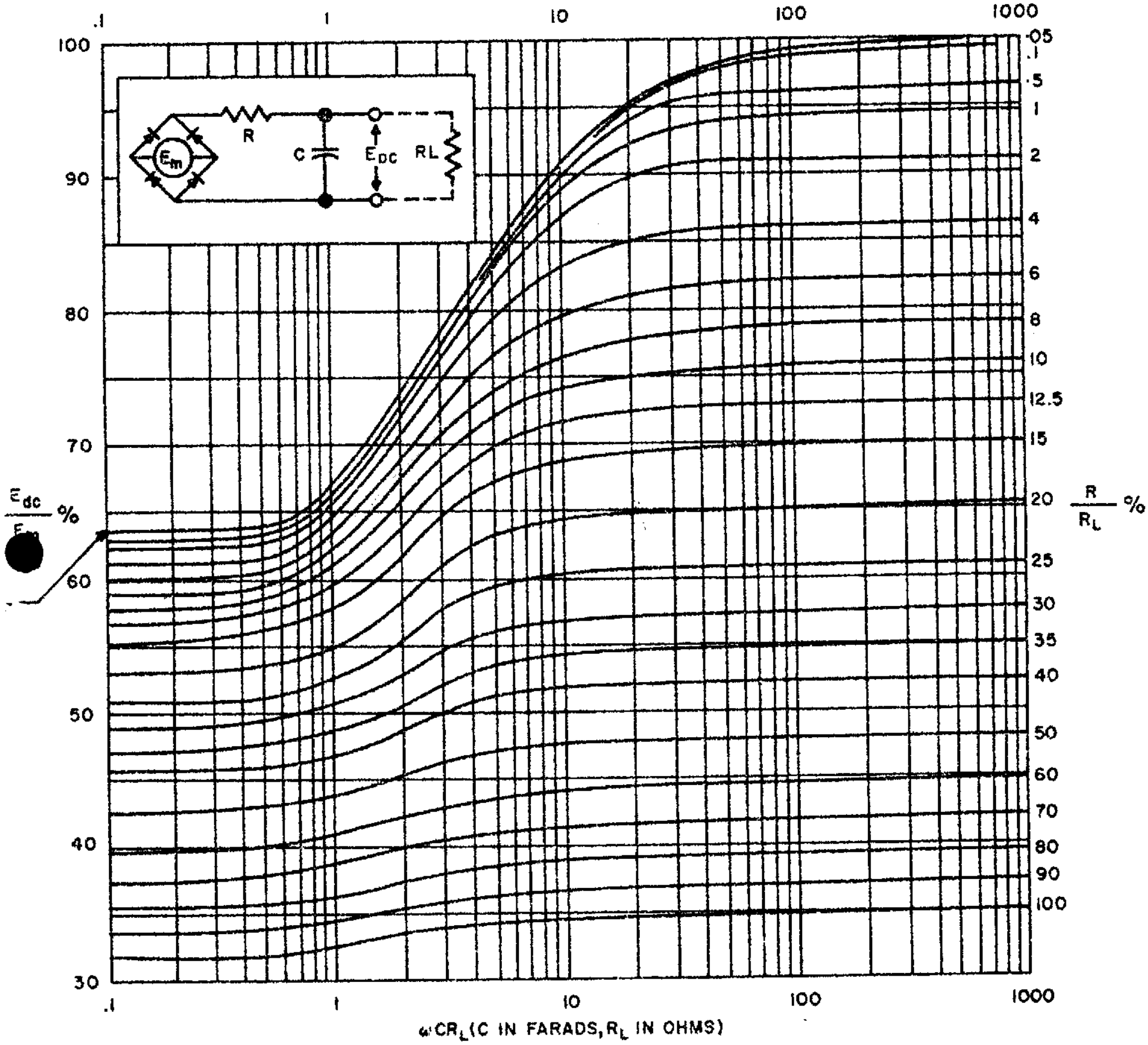


FIGURE 7

Voltage Ratio For Full-Wave Capacitor Input Filter Circuit
(From O. H. Schade, Proceedings IRE, July, 1943, by permission)

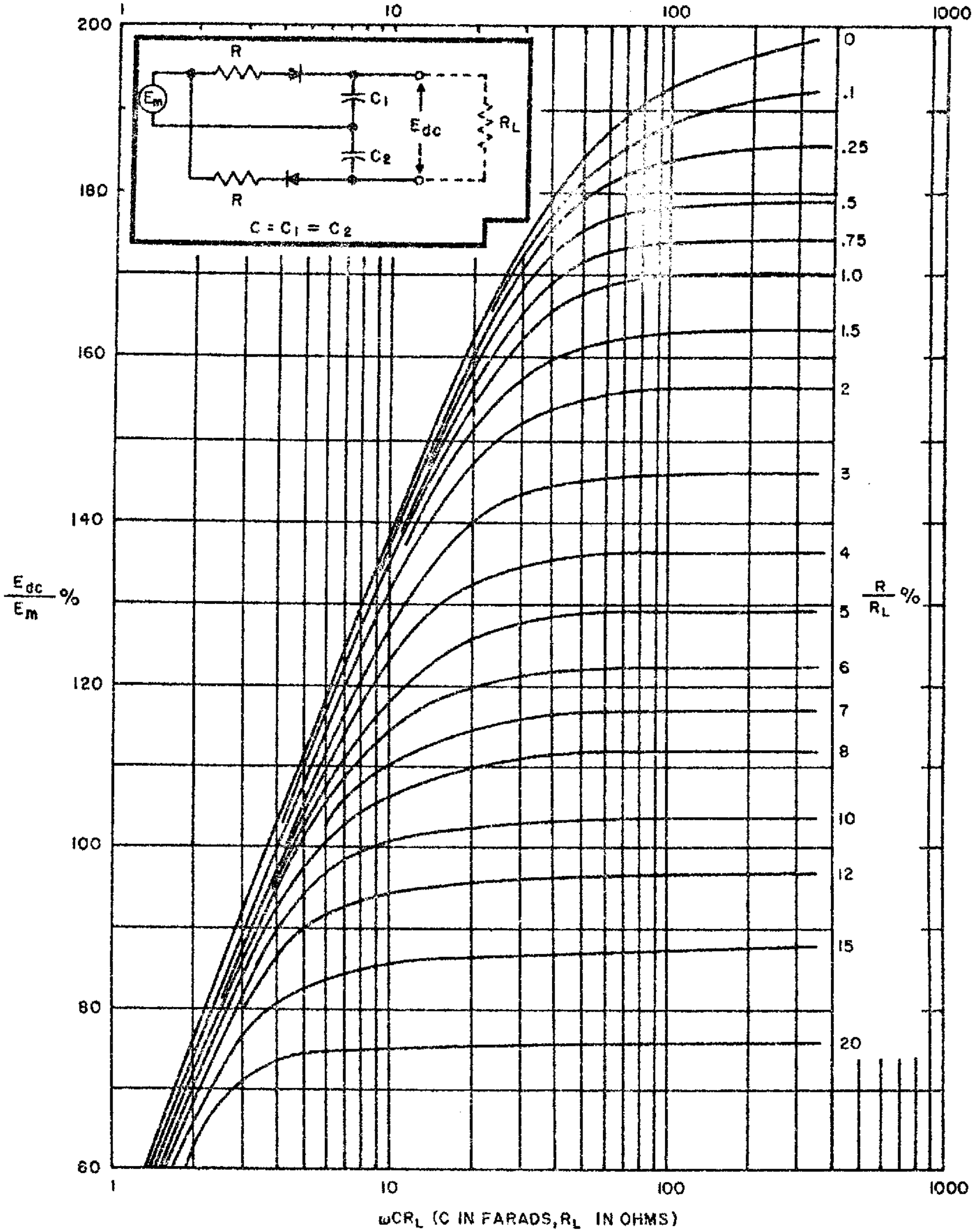


FIGURE 8

Voltage Ratio For Voltage Doubling Capacitor Input Filter Circuits
(From O. H. Schade, Proceedings IRE, July, 1943, by permission)

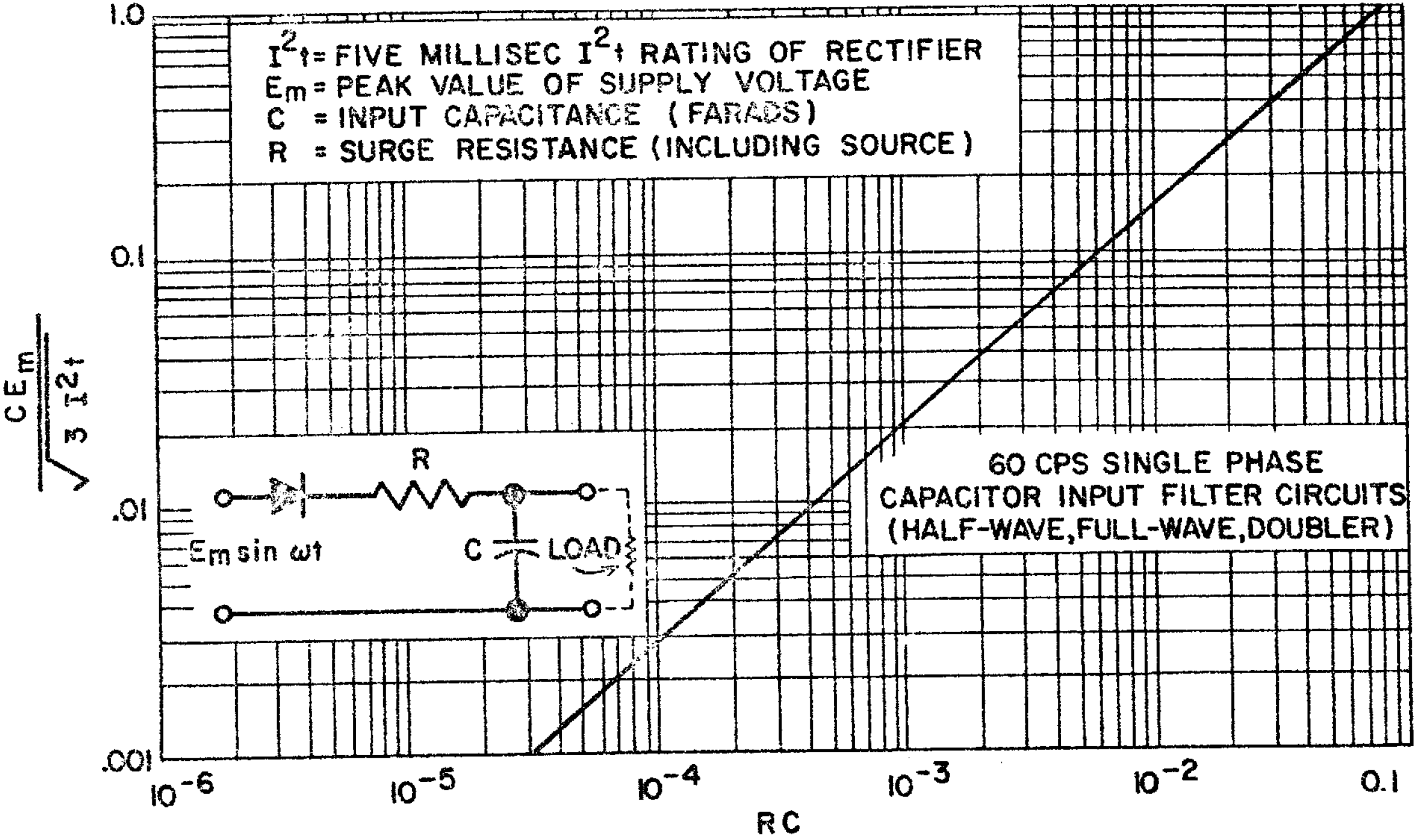


FIGURE 9

Required Charging Time Constant Versus Diode I^2t Capability

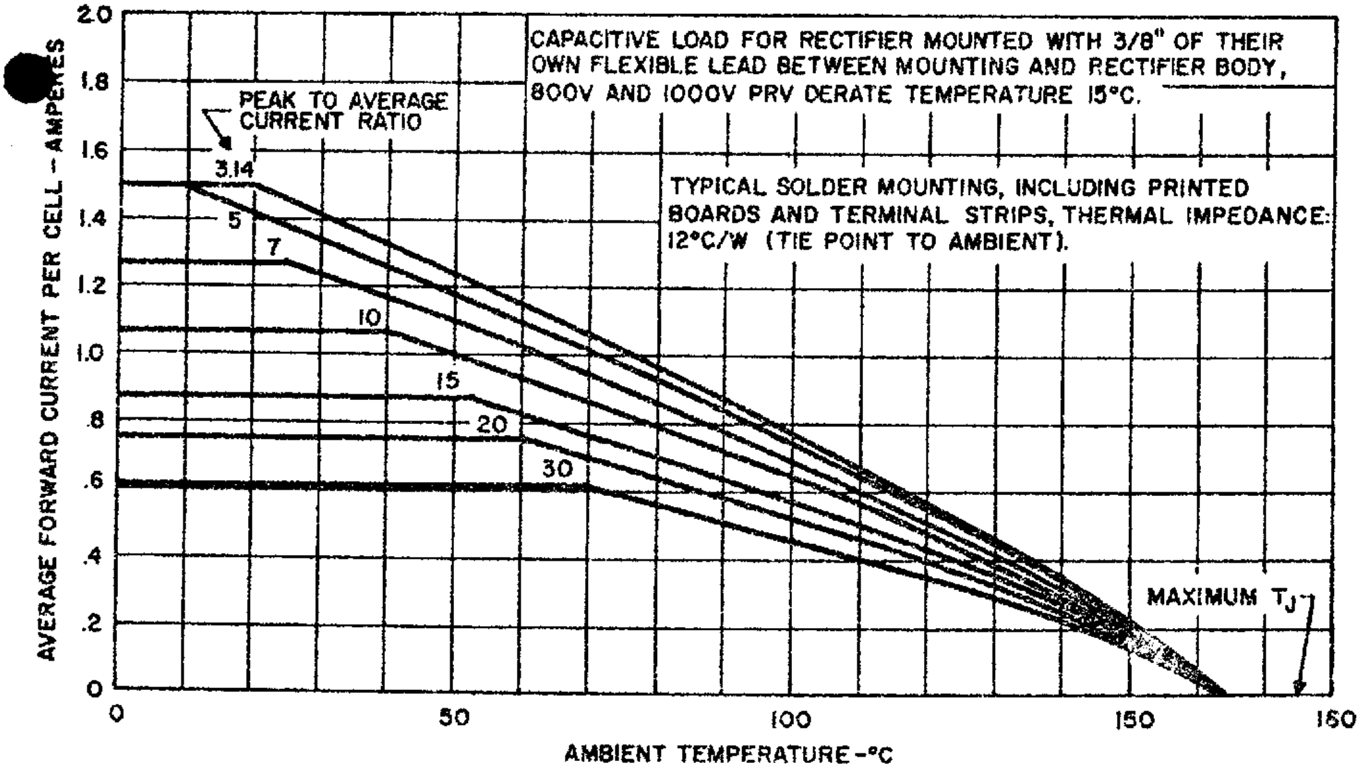


FIGURE 10
Typical Rectifier Diode Capacitive Filter Duty Rating Curve
In Terms of Peak-to-Average Current Ratio

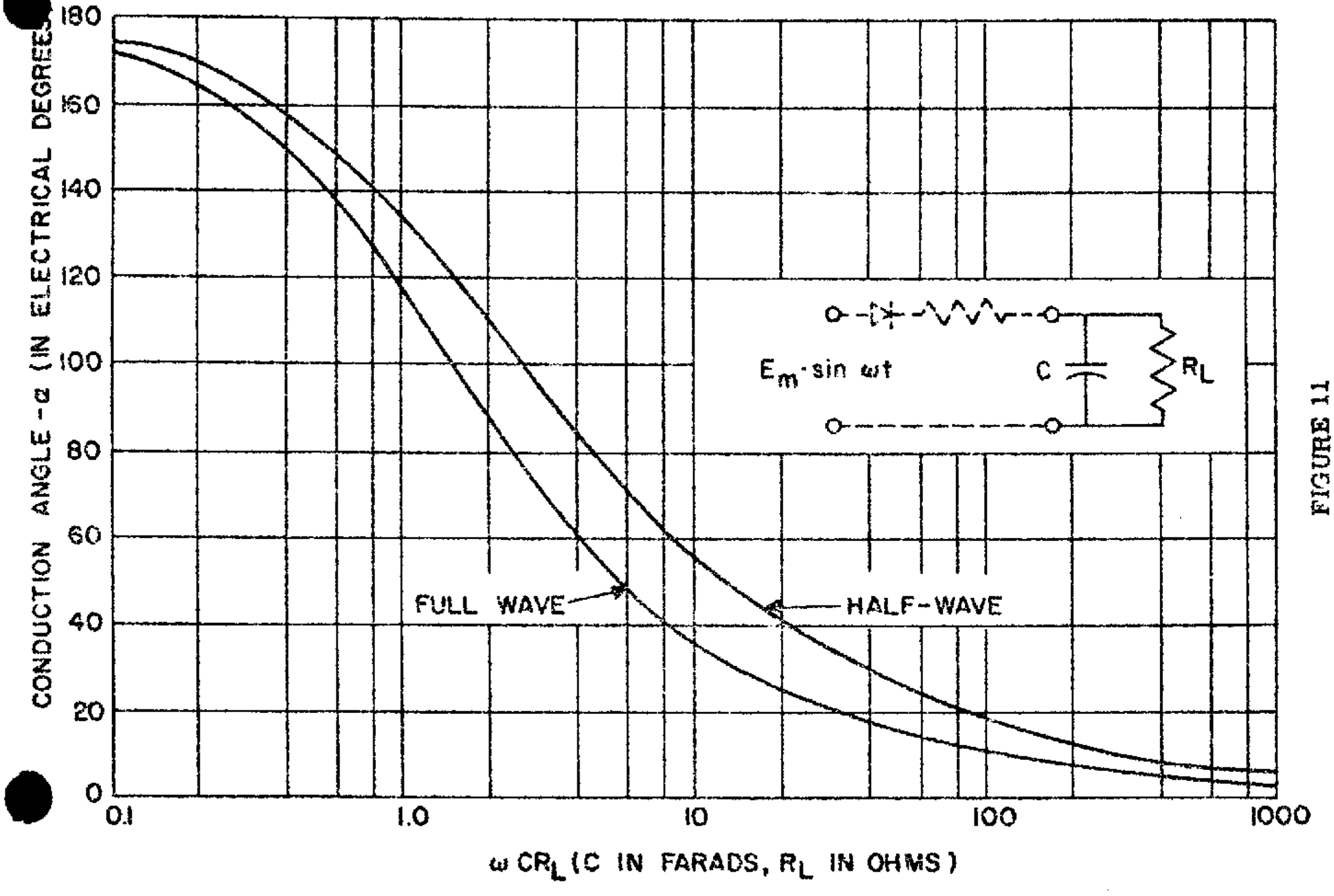


FIGURE 11
Rectifier Diode Current Conduction Angle
vs ωCR_L