time. Successive applications of test voltage are usually made at either decreased voltage or decreased time. In view of their dubious value, repeated insulation tests are best omitted.

Corona tests are not open to this objection. A voltage 5 per cent higher than normal is applied to the winding, and the leads are run through blocking capacitors to the input of a sensitive radio receiver as in Fig. 38.[1] RETMA standard noise values for this test are based primarily on radio reception, but they do indicate whether standard insulation practice is followed. See Table X.

TABLE X. CORONA VOLTAGE

RMS Working Voltage (kilovolts)	Corona Level (microvolts)
Up to 8.6	1,000
8.61 to 15	2,500

Transformers which are subjected to voltage surges may be given impulse tests to determine whether the insulation will withstand the surges. Power line surges are the most difficult to insulate for. The electric power industry has standardized on certain impulse voltage magnitudes and wave shapes for this testing.[2] The ratio of impulse voltage magnitude to 60-cycle, 1-minute insulation test voltage is called the *impulse ratio*. This ratio is much greater for oil-insulated transformers than for dry-type transformers, and is discussed further in Chapter 4.

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[1] See RETMA Standard TR-102-B, "Power Transformers for Radio Transmitters."

[2] See ASA Standard C57.22-1948, paragraph 22.116.

4. RECTIFIER PERFORMANCE

46. Ripple. Filters used with rectifiers allow the rectified direct current to pass through to the load without appreciable loss, but ripple in the rectified output is attenuated to the point where it is not objectionable. Filtering sometimes must be carried out to a high degree. From the microphone to the antenna of a high-power broadcast station, there may be a power amplification of 2×10^{15}. The introduction of a ripple as great as 0.005 per cent of output voltage at the microphone would produce a noise in the received wave loud enough to spoil the transmitted program. A rectifier used at the low-power levels must be unusually well filtered to prevent noticeable hum from being transmitted.

Different types of rectifiers have differing output voltage waves, which affect the filter design to a large extent. Certain assumptions, generally permissible from the standpoint of the filter, will be made in order to simplify the discussion. These assumptions are:

1. The alternating voltage to be rectified is a sine wave.
2. The rectifying device passes current in one direction but prevents any current flow in the other direction.
3. Transformer and rectifier voltage drops are negligibly small.
4. Filter condenser and reactor losses are negligible.

47. Single-Phase Rectifiers. Single-phase half-wave rectified voltage across a resistive load R is shown in Fig. 77. It may be resolved by Fourier analysis into the direct component whose value is $0.318E_{pk}$ or $0.45E_{ac}$, and a series of alternating components. The fundamental alternating component has the same frequency as that of the supply.

Single-phase half-wave rectifiers are used only when the low average value of load voltage and the presence of large variations in this voltage are permissible. The chief advantage of this type of rectifier is its simplicity. A method of overcoming both its disadvantages is illustrated in Fig. 78 where a capacitor C shunts the load. By using the proper capacitor, it is often possible to increase the value of E_{dc} to within a few per cent of the peak voltage E_{pk}. The principal disadvantage of this method of filtering is the large current drawn by the capacitor during the charging interval as shown in Fig. 49(*b*) (p. 63). This current is limited only by transformer and rectifier regulation; yet it must not be so large as to cause damage to the rectifier. The higher the value of E_{dc} with respect to E_{ac}, the larger is the charging current taken by C. (See Figs. 50 and 52, pp. 64 and 66.) Therefore, if a smooth current wave is desired, some other method of filtering must be used.

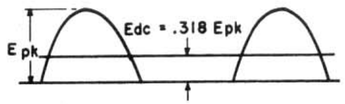

FIG. 77. Half-wave rectifier voltage.

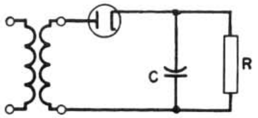

FIG. 78. Capacitor filter.

To obtain less voltage variation or ripple amplitude, after the limiting capacitor size has been reached, an inductive reactor may be employed. It may be placed on either the rectifier or the load side of the capacitor, depending on whether the load resistance R is high or low respectively. See Figs. 79(*a*) and (*b*). In the former, the voltage E_{dc} has less than the average value $0.45E_{ac}$, because the inductor delays the build-up of current during the positive half-cycle of voltage, and yet the inductor in this case should have a high value of reactance X_L, compared to the capacitive reactance X_C, in order to filter effectively. When R is low, reactance X_L should be high compared to R.

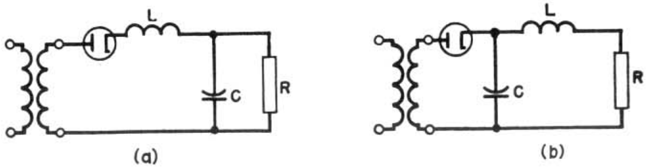

FIG. 79. (*a*) Inductor-input filter; (*b*) capacitor-input filter.

In Fig. 79(*a*) the ripple amplitude across R is $-X_C/(X_L - X_C)$ times the amplitude generated by the rectifier, if R is high compared to X_C. Also, in Fig. 79(*b*), the ripple amplitude across R is R/X_L times the ripple obtained with capacitor only. R here is small compared to X_L.

Large values of inductance are required to cause continuous current flow when the inductor is on the rectifier side of the capacitor in a half-wave rectifier circuit. Since current tends to flow only half the time, the rectified output is reduced accordingly. This difficulty is eliminated by the use of the full-wave rectifier of Fig. 80. The alternating components of the output voltage have a fundamental frequency double that of the supply, and the amplitudes of these components are much less than for the half-wave rectifier. The higher ripple frequency causes L and C to be doubly effective; the smaller amplitude results in smaller percentage of ripple input to the filter. Current flow is continuous and E_{dc} has double the value that it had in Fig. 77. For these reasons, this type of rectifier is widely used.

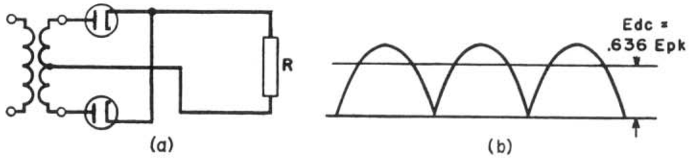

FIG. 80. (*a*) Single-phase full-wave rectifier; (*b*) rectified full-wave voltage.

A full-wave rectifier uses only one-half of the transformer winding at a time; that is, E_{ac} is only half the transformer secondary voltage. A circuit which utilizes the whole of this voltage in producing E_{dc} is the single-phase bridge rectifier shown in Fig. 81. The output voltage relations are the same as those of Fig. 80(*b*). Although this circuit requires more rectifying tubes, it eliminates the need for a transformer midtap.

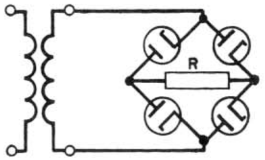

FIG. 81. Bridge rectifier.

48. Polyphase Rectifiers. The effect of rectifying more than one phase is to superpose more voltages of the same peak value but in different time relation to each other. Figures 82(*a*) and (*b*) give a comparative picture of the rectified output voltage for three-phase half-wave and full-wave rectifiers. Increasing the number of phases increases the value of E_{dc}, increases the frequency of the alternating components, and decreases the amplitude of these components. Ripple frequency is p times that of the unrectified alternating voltage, p being 1, 2, 3, and 6 for the respective waves. Roughly speaking, p may be taken to represent the number of phases, provided that due allowance is made for the type of circuit, as in Fig. 83. Rectifiers with $p = 3$ or 6 are derived from three-phase supply lines, and, by special connections, rectifiers with $p = 9$, 12, or more are obtained.

The frequency of any ripple harmonic is mp, where m is the order of the harmonic.

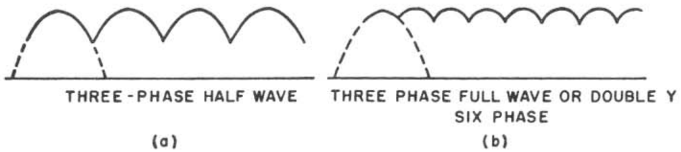

FIG. 82. Polyphase rectifier output waves.

Ripple voltage for any of these rectifiers can be found by the Fourier relation:

$$A_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos n\omega t\, dt \tag{45}$$

where A_n = amplitude of nth ripple harmonic
T = ripple fundamental period
t = time (with peak of rectified wave as $t = 0$)
$\omega = 2\pi/Tp = 2\pi \times$ supply line frequency
$f(t)$ = ripple as a function of time
$= E_{pk} \cos \omega t,\ T/2 > \omega t > -T/2.$

The voltage peak is chosen as $t = 0$ to obtain a symmetrical function $f(t)$ and eliminate a second set of harmonic terms like those in equation 45, but with sin $n\omega t$ under the integral.

Ripple amplitude is given in Fig. 83 for the ripple fundamental, and second and third harmonics with reactor-input filters. In this curve, the ratio P_A of ripple amplitude to direct output voltage is plotted against the number of phases p. It should be noted that P_A diminishes by a considerable amount for the second and third harmonics. In general, if a filter effectively reduces the percentage of fundamental ripple across the load, the harmonics may be considered negligibly small.

49. Multistage Filters. In the inductor-input filter shown in Fig. 79(a), the rectifier is a source of non-sinusoidal alternating voltage connected across the filter. It is possible to replace the usual circuit representation by Fig. 84(a). For any harmonic, say the nth, the voltage across the whole circuit is the harmonic amplitude A_n, and the voltage across the load is $P_R E_{dc}$, P_R being ripple allowable across the load, expressed as a fraction of the average voltage. Since the load

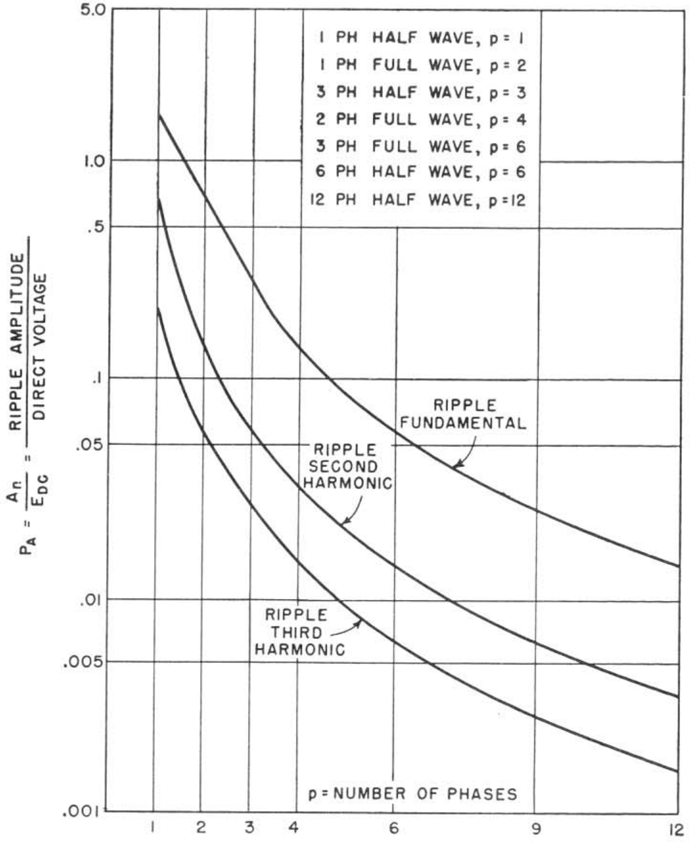

FIG. 83. Rectifier ripple voltage.

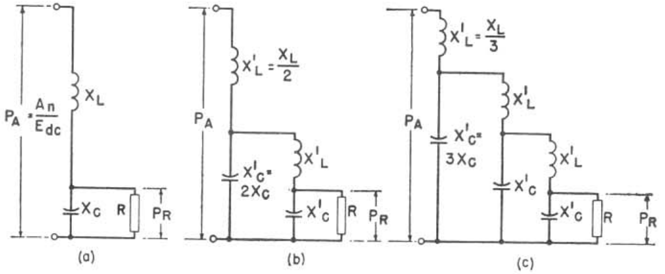

FIG. 84. Inductor-input filter circuits.

resistance R is high compared to X_C, the two voltages are nearly in phase, and they bear the same ratio to each other as their respective reactances, or

$$\frac{P_A}{P_R} = \frac{X_L - X_C}{X_C} = \frac{X_L}{X_C} - 1 \tag{46}$$

From the type of rectifier to be used, and the permissible amount of ripple in the load voltage, it is possible to determine the ratio of inductive to capacitive reactance.

When the magnitude P_R must be kept very small, the single-stage filter of Fig. 84(a) may require the inductor and the capacitor to be abnormally large. It is preferable under this condition to split both the inductor and the capacitor into two separate equal units, and connect them like the two-stage filter of Fig. 84(b). A much smaller total amount of inductance and of capacitance will then be necessary. For this filter

$$\frac{P_A}{P_R} = \left(\frac{X'_L - X'_C}{X'_C}\right)^2 \tag{47}$$

X'_L and X'_C being the reactances of each inductor and capacitor in the circuit. Likewise, the three-stage filter of Fig. 84(c) may be more practicable for still smaller values of P_R. In the latter filter,

$$\frac{P_A}{P_R} = \left(\frac{X'_L - X'_C}{X'_C}\right)^3 \tag{48}$$

and, in general, for an n-stage filter,

$$\frac{P_A}{P_R} = \left(\frac{X'_L - X'_C}{X'_C}\right)^n \tag{49}$$

It is advantageous to use more than one stage only if the ratio P_A/P_R is high. That the gain from multistage filters is realized only for certain values of P_A/P_R is shown by Fig. 85. The lower curve shows the relation between P_A/P_R and X_L/X_C for a single-stage filter. The second curve shows the increase in P_A/P_R gained by splitting up the same amount of L and C into a two-stage filter; as indicated in Fig. 84(b), the inductor and capacitor both have one-half their "lumped" value. The upper curve indicates the same increase for a three-stage filter, each inductor and capacitor of which have one-third of their "lumped" or single-stage filter value. The attenuation in multistaging is enormous for high X_L/X_C. For lower ratios there may be a loss instead of a gain, as shown by the intersection of the two upper curves. These curves intersect the lower curve if all are prolonged further to the left. This may be a puzzling condition; but consider that, for $X_L/X_C = 50$ in the single-stage filter, the ratio is

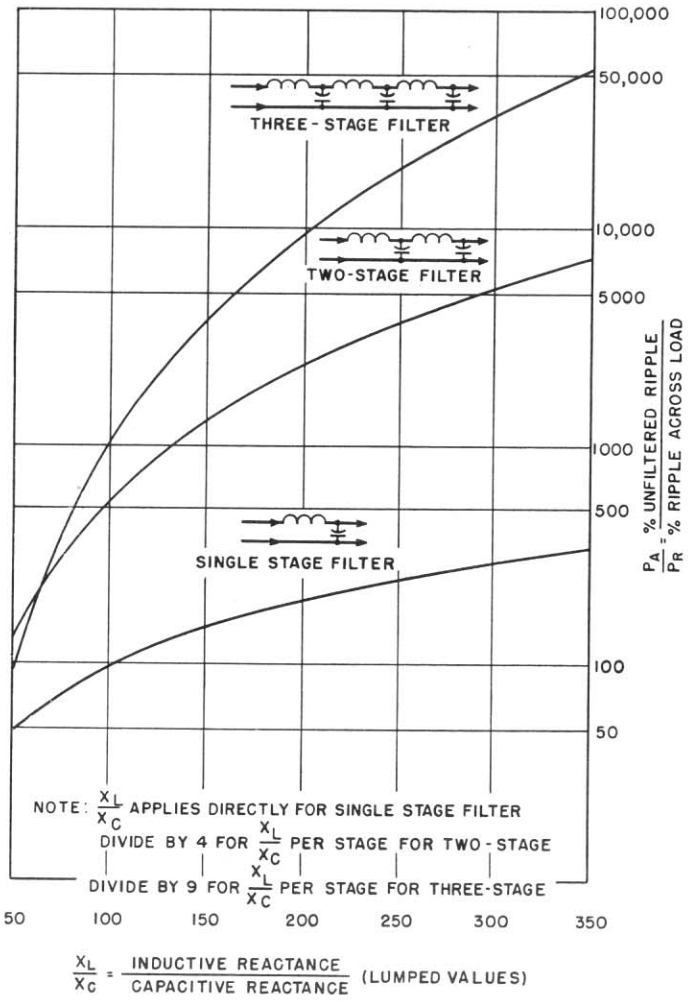

FIG. 85. Attenuation in one-, two-, and three-stage filters.

$\frac{1}{3}X_L/3X_C$ or 5% in the three-stage filter; the rather small advantage in the latter is not difficult to account for.

Other factors may influence the number of filter stages. In some applications, modulation or keying may require that a definite size of filter capacitor be used across the load. Usually these conditions result in a single-stage filter, where otherwise more stages might be most economical.

Table VII (p. 62) shows filter reactors in the negative lead, which may be either at ground or high potential. If low ripple is required in the filtered output, it is usually preferable to locate the filter reactors in the high-voltage lead. Otherwise, there is a ripple current path through the anode transformer winding capacitance to ground which bypasses the filter reactor. Ripple then has a residual value which cannot be reduced by additional filtering. In the three-phase, zigzag, full-wave circuit, with center tap used for half-voltage output, separate reactors should be used in the positive leads; placing a common reactor in the negative lead introduces high amplitude ripple in the high-voltage output.

In rectifiers with low ripple requirements, both filament and anode windings should be accurately center-tapped to avoid low-frequency ripple, which is difficult to filter. Three-phase leg voltages should be balanced for the same reason.

50. Capacitor-Input Filters. One of the assumptions implied at the beginning of this chapter, namely, that transformer and rectifier voltage drops are negligibly small, cannot usually be made when capacitor-input filters are used, because of the large peak currents drawn by the capacitor during the charging interval. Such charging currents drawn through finite resistances affect both the d-c output voltage and the ripple in a complicated manner, and simple analysis such as that given for inductor-input filters is no longer possible. Figure 86 is a plot of the ripple in the load of capacitor-input filters with various ratios of source to load resistance, and for three types of single-phase rectifiers. These curves are useful also when resistance is used in place of an inductor at the input of a filter. ω is 2π times the a-c supply frequency, C is the capacitance, R_L is the load resistance, and R_S the source resistance.

When L-C filter stages follow a capacitor-input filter, the ripple of the latter is reduced as in Fig. 85, except that the value of P_A must be taken from Fig. 86. When an R-C filter stage follows any type of filter,

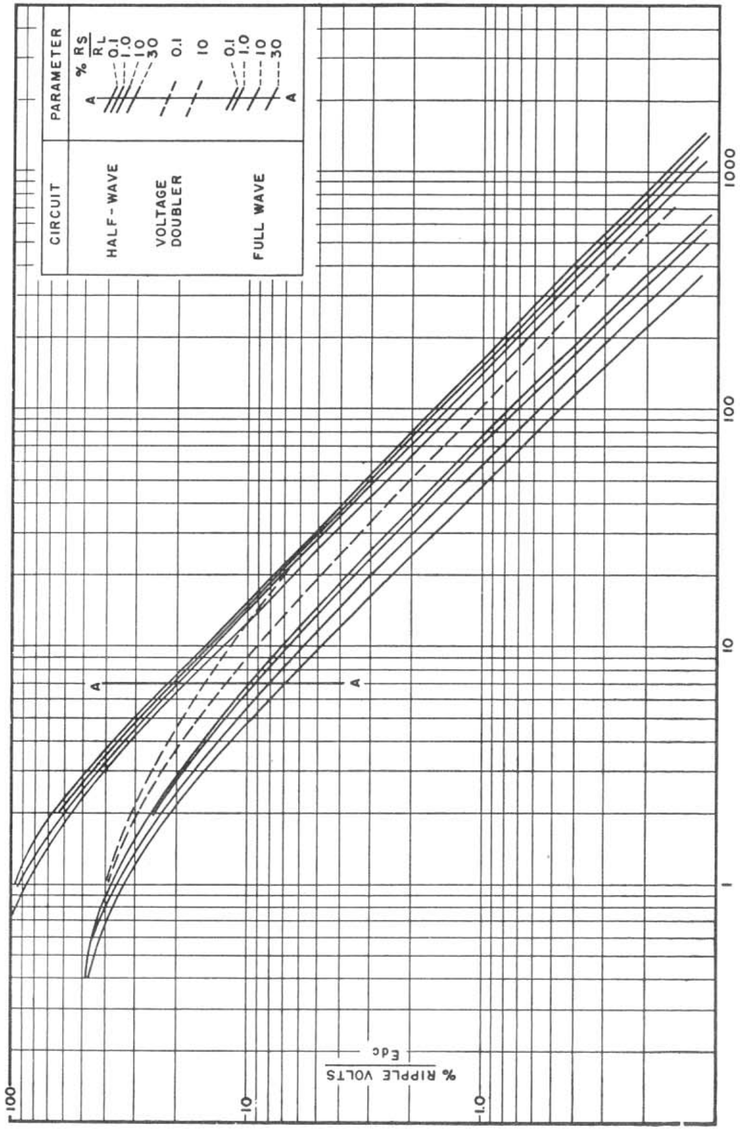

Fig. 86. Rms ripple voltage of capacitor-input filters.

the ripple is reduced in the ratio R/X_C represented by the R-C stage.

51. Rectifier Regulation. The regulation of a rectifier comprises three distinct components:

1. The d-c resistance or IR drop.
2. The commutation reactance or IX drop.
3. The capacitor charging effect.

The first component can be reduced to a small value by the use of tubes, transformers, and inductors having low resistance. Mercury-vapor tubes are of noteworthy usefulness in this respect, as the internal voltage drop is low and almost independent of load current variations.

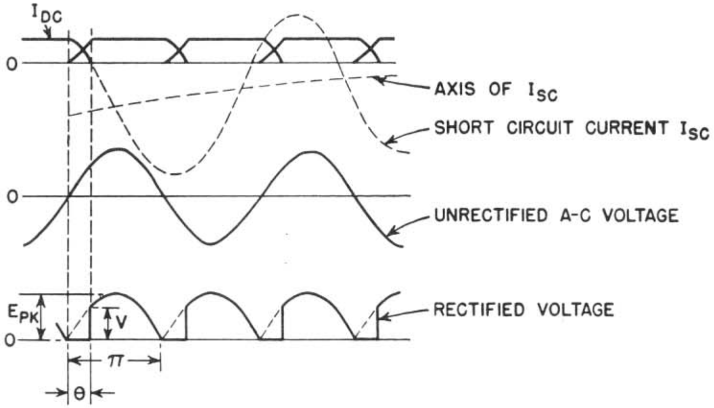

FIG. 87. Commutation current effect on rectifier voltage.

Commutation reactance can be kept to a low value by proper transformer design, particularly where the ratio of short-circuit current to normal load is high.

During part of each cycle, both tubes of a single-phase full-wave rectifier are conducting. During this interval one tube loses its current and the other one builds up to normal current. Because of the inevitable reactance in the transformer, this change does not take place immediately but during an angle θ as in Fig. 87. Short-circuit current is initiated which would rise as shown by the dotted lines of Fig. 87, if it could pass through the rectifier tubes; it prevents the rectified voltage wave from retaining its normal shape, so that for a portion of each cycle the rectified output is zero.

Let the transformer winding resistance be temporarily neglected; if the current could rise to maximum, the short-circuit value would be

$2E_{pk}/X$, where X is the leakage reactance of the whole secondary, but it is limited by the rectifier to I_{dc}. The short-circuit current rises to $(1 - \cos\theta)$ times maximum in the commutation period, or

$$[2E_{pk}(1 - \cos\theta)]/X = I_{dc}$$

The average voltage from zero to the re-ignition point V is

$$(E_{pk}/\pi)(1 - \cos\theta)$$

Combining these relations gives, for the *average* voltage cut out of the rectified voltage wave by commutation,

$$V_{\text{av}} = I_{dc}X/2\pi \tag{50}$$

By similar reasoning, the commutation reactance drop for polyphase rectifiers is

$$pI_{dc}X'/2\pi \tag{51}$$

where X' = the transformer leakage reactance from line to neutral on the secondary side, and p = the number of phases in Fig. 83.

In this formula, the leakage reactance per winding is associated with the voltage across that winding. This is accurate when each phase is supplied by a separate transformer. But it fails for $p = 2$ in the single-phase full-wave rectifier, using one plate transformer, where half of the secondary voltage is rectified each half-cycle. In such a rectifier, during commutation the whole secondary voltage is effective, and so is the leakage reactance of the whole secondary. This reactance has 4 times the leakage reactance of each secondary half-winding, but only twice the half-winding voltage acts across it. Hence equation 50 must be used for the single-phase rectifier; here X = the reactance of the entire secondary.

When high winding resistance limits short-circuit current, commutation has less effect than equation 50 would indicate. This condition prevails in small rectifiers; the IX drop is negligibly small because of the small transformer dimensions. For example, in the plate transformer designed in Fig. 58 the leakage inductance is 0.166 henry. The commutation reactance drop is, from equation 50,

$$0.115 \times 0.166 \times 2\pi \times 60/2\pi = 1.15 \quad \text{volts}$$

or 0.1 per cent. This is negligible compared to the 3.7 per cent regulation calculated in Fig. 58. In this case the short-circuit current would be limited by winding resistance rather than by leakage inductance.

In large rectifiers, all rectifier components have low losses to prevent power wastage or overheating, and the IR drop is a very small percentage of the total. At the same time, a large transformer requires careful design in order to keep the IX drop reasonably small. Therefore, in large rectifiers the IX drop is the dominant cause of regulation. An example with 60 kva rating has 0.7 per cent IR drop and 6 per cent IX drop.

In medium-size rectifiers the IR and IX drops may be of equal, or at least comparable, value. In such rectifiers these two components of regulation do not add arithmetically. Commutation interval θ, Fig. 87, depends on the short-circuited reactance when resistance is negligible, but if resistance is appreciable θ is related to the ratio X/R exponentially.[1] The increase in regulation caused by commutation reactance may be found from Fig. 88, in terms of d-c output voltage E_{dc}. In this figure the regulation of three widely used rectifiers (single-phase full-wave, three-phase half-wave, and three-phase full-wave) is given in a manner which enables one to proceed directly from the IR component of regulation to total regulation.

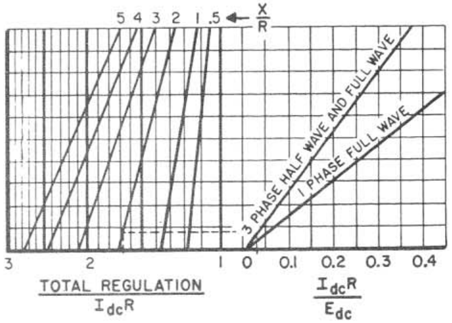

FIG. 88. Increase in rectifier regulation due to transformer reactance.

X and R are ohms per phase except X/R ratio is for the whole secondary in single-phase full-wave rectifiers. R in X/R ratio includes primary R in all cases. R in $I_{dc}R/E_{dc}$ is for two windings in three-phase full-wave rectifiers. To obtain total regulation, project $I_{dc}R/E_{dc}$ vertically to one-phase or three-phase line. Project this point to the left to proper X/R line. Abscissa at left gives total regulation. An example is indicated by the dotted line. In this example, the rectifier is three-phase full-wave.

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[1] See *Mercury-Arc Rectifiers and Their Circuits*, by D. C. Prince and P. B. Vogdes, McGraw-Hill Book Co., New York, 1927, p. 216.

$$\begin{aligned} E_{dc} &= 2{,}000 \text{ volts} & \frac{X}{R} &= 2 \\ I_{dc} &= 1 \text{ amp} & & \\ R &= 60 \text{ ohms} & \frac{I_{dc}R}{E_{dc}} &= \frac{60}{2{,}000} = 3 \text{ per cent} \\ X &= 120 \text{ ohms} & & \end{aligned}$$

Total regulation = $1.68 \times 3 = 5.04$ per cent. If the IX regulation had been added directly to IR it would be 6 per cent + 3 per cent = 9 per cent, and the calculated regulation would be nearly 4 per cent higher than actual.

52. Capacitor Effect. If the rectifier had no filter capacitor, the rectifier would deliver the average value of the rectified voltage wave, less regulation components 1 and 2 of Section 51. But with a filter capacitor, there is a tendency at light loads for the capacitor to charge up to the peak value of the rectified wave. At zero load, this amounts to 1.57 times the average value, or a possible regulation of 57 per cent in addition to the IR and IX components, for single-phase full-wave rectifiers. This effect is smaller in magnitude for polyphase rectifiers, although it is present in all rectifiers to some extent.

Suppose that the rectifier circuit shown in Fig. 80(a) delivers single-phase full-wave rectifier output as shown in Fig. 80(b) to an inductor-input filter and thence to a variable load. In such a circuit, the filter inductor keeps the capacitor from charging to a value greater than the average E_{dc} of the rectified voltage wave at heavy loads. At light loads the d-c output voltage rises above the average of the rectified wave, as shown by the typical regulation curve of Fig. 89.

Starting at zero load, the d-c output voltage E_0 is 1.57 times the average of the rectified wave. As the load increases, the output voltage falls rapidly to E_1 as the current I_1 is reached. For any load greater than I_1, the regulation is composed only of the two components IR and IX. It is good practice to use a bleeder load I_1 so that the rectifier operates between I_1 and I_2.

Filter elements X_L and X_C determine the load I_1 below which voltage rises rapidly. The filter, if it is effective, attenuates the a-c ripple voltage so that across the load there exists a d-c voltage with a small ripple voltage superposed. A choke-input filter attenuates the harmonic voltages much more than the fundamental, and, since the harmonics are smaller to begin with, the main function of the filter is to take out the fundamental ripple voltage. This has a peak value, according to Fig. 83, of 66.7 per cent of the average rectified d-c voltage for a single-phase full-wave rectifier. Since this ripple is purely a-c it encounters a-c impedances in its circuit. If we designate the choke impedance as X_L, and the capacitor impedance as X_C, both at the fundamental ripple frequency, the impedance to the fundamental component is $X_L - X_C$, the load resistance being negligibly high compared to X_C in an effective filter. The d-c voltage, on the other hand, produces a current limited mainly by the load resistance, provided that the choke *IR* drop is small.

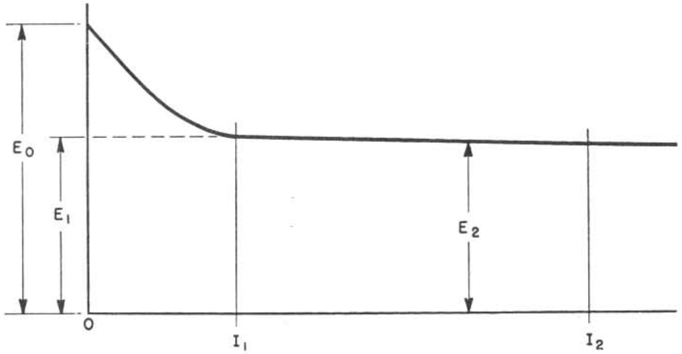


FIG. 89. Rectifier regulation curve.

A-c and d-c components are shown in Fig. 90, with the ripple current I_{ac} superposed on the load direct current I_{dc}. If the direct current is made smaller by increased load resistance, the a-c component is not affected because load resistance has practically no influence in determining its value. Hence a point will be reached, as the d-c load current is diminished, where the peak value of ripple current just equals the load direct current. Such a condition is given by d-c load I_1 which is equal to I_{ac}. If the d-c load is reduced further, say to the value I_x, no current flows from the rectifier in the interval *A-B* of each ripple cycle. The ripple current is not a sine wave, but is cut off on the lower halves, as in the heavy line of Fig. 91. Now the average value of this current is not I_x but a somewhat higher current I_y. That is, the load direct current is higher than the average value of the rectified sine wave voltage divided by the load resistance. This increased current is caused by the tendency of the capacitor to charge up to the peak of the voltage wave between such intervals as *A-B*; hence the

term capacitor effect which is applied to the voltage increase. The limiting value of voltage is the peak value of the rectified voltage, which is 1.57 times the sine-wave average, at zero load current.

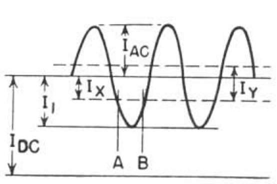


FIG. 90. A-c and d-c components of filter current.

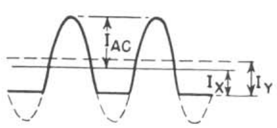


FIG. 91. Capacitor effect at light load.

To prevent capacitor effect the choke must be large enough so that I_{ac} is equal to or less than the bleeder current I_1. This consideration leads directly to the value of choke inductance. The bleeder current I_1 is E_1/R_1, where R_1 is the value of bleeder resistance. The ripple current is the fundamental ripple voltage divided by the ripple circuit impedance, or

$$I_{ac} = \frac{0.667E_1}{X_L - X_C}$$

Equating I_1 and I_{ac} we have, for a single-phase full-wave rectifier,

$$R_1 = \frac{X_L - X_C}{0.667} \tag{52}$$

Here we see that the value of capacitance also has an effect, but it is minor relative to that of the choke. In a well-designed filter, the choke reactance X_L is high compared to X_C. Therefore, the predominant element in fixing the value of R_1 (and of I_1) is the filter reactor.

Polyphase rectifiers have similar effects, but the rise in voltage is not so great because of the smaller difference between peak and average d-c output. The bleeder resistance for eliminating capacitor effect can be found in general from

$$R_1 = \frac{X_L - X_C}{P_1} \tag{53}$$

where P_1 is the fundamental ripple peak amplitude from Fig. 83, and X_L and X_C are the filter reactances at fundamental ripple frequency.

Between load I_1 and zero load, the rate of voltage rise depends upon the filter. Figure 92 shows the voltage rise as a function of the ratio

$(X_L - X_C)/R_L$ for a single-phase full-wave rectifier. A curve of ripple in terms of ripple at full load is given. Figure 92 is a plot of experimental data taken on a rectifier with $IR + IX$ regulation of 5 per cent. Reactances X_L and X_C are computed for the fundamental ripple frequency.

Capacitor-input filters have the voltage regulation curves shown in Figs. 50, 51, and 53) (pp. 64, 65, and 68) for their respective circuits. At light loads these filters may give reasonably good regulation, but it is possible to get very poor regulation at heavier loads, as can be seen from the curves. Rectifier series resistance plays an important part in the voltage regulation of this type of filter. The effect of anode transformer leakage inductance can be found from Fig. 92.

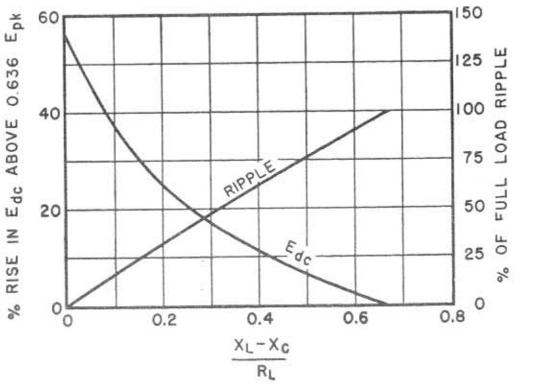


FIG. 92. Voltage rise in single-phase full-wave rectifier at light loads.

53. Tuned Rectifier Filters. Sometimes an inductor-input filter is tuned as in Fig. 93. The addition of capacitor C_1 increases the effective reactance of the inductor to the fundamental ripple frequency. Both regulation and ripple of this type of filter are improved. The filter is not tuned for the ripple harmonics, so the use of high-Q filter inductors is unnecessary. An increase in effectiveness of the filter inductor of about 3 to 1 can be realized in a single-phase full-wave rectifier circuit. Tuned filters are less effective with three-phase rectifiers because slight phase unbalance introduces low-frequency ripple which the filter does not attenuate.

Filters may be tuned as in Fig. 94, where the filter capacitor C_1 is connected to a tap near the right end of inductor L, and the other filter capacitor C_2 is chosen to give series resonance and hence zero reactance across the load at the fundamental ripple frequency. Because of choke losses, the impedance across R_L is not zero, but the resulting ripple across load resistor R_L can be made lower than without the use of capacitor C_1. Ripple is attenuated more than in the usual inductor-input filter, but regulation is not substantially different.

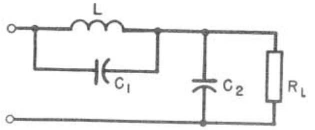


FIG. 93. Shunt-tuned filter.

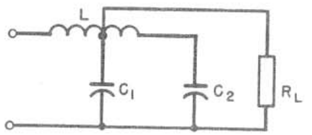


FIG. 94. Series-tuned filter.

54. Rectifier Currents. If the inductor in an inductor-input filter were infinitely large, the current through it would remain constant. If the commutation reactance effect is not considered, the current through each tube of a single-phase rectifier would be a square wave, as shown by I_1 and I_2 of Fig. 49(*a*) (p. 63). The peak value of this current wave is the same as the d-c output of the rectifier, and the rms value is $0.707I_{dc}$. With finite values of inductance, an appreciable amount of ripple current flows through the inductor and effectively modulates I_1 and I_2, thus producing a larger rms inductor current like the first wave of Table I (p. 16).

Capacitor-input filters draw current from the rectifier only during certain portions of the cycle, as shown in Fig. 49(*b*). For a given average direct current, the peak and rms values of these current waves are much higher than for inductor-input filters. Values for the single-phase rectifiers are given in Fig. 52 (p. 66). If an L-C filter stage follows the input capacitor, the inductor rms current is the output direct current plus the ripple current in quadrature.

Polyphase rectifiers are ordinarily of the choke-input type, because they are used mostly for larger power, and therefore any appreciable amount of series resistance cannot be tolerated. For this reason, the low IR drop tubes, such as mercury-vapor rectifiers, are commonly used. Such tubes do not possess sufficient internal drop to restrict the peak currents drawn by capacitor-input filters to the proper values.

In a shunt-tuned power supply filter such as shown in Fig. 93, the current drawn from the rectifier is likely to be peaked because two capacitors C_1 and C_2 are in series, without intervening resistance or inductance. This peak quickly subsides because of the influence of inductor L, but an oscillation may take place on top of the tube current wave as shown in Fig. 95. The rectifier tube must be rated to withstand this peak current. At the end of commutation the voltage jumps suddenly from zero to V (Fig. 87). Peak rectifier current may be as much as

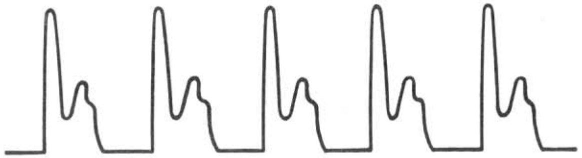


FIG. 95. Anode current with shunt-tuned filter.

$$I_{pk} = V/\omega L_s \tag{54}$$

L_s is half the transformer leakage inductance, and $\omega = 2\pi \times$ frequency of oscillation determined by L_s in series with C_1 and C_2. This peak current is superposed on I_{dc}. It flows through the anode transformer and tube, but the current in choke L (Fig. 93) is determined by ripple voltage amplitude and choke reactance. Series resistance R_s reduces this peak current to the value

$$I_{pk} = \frac{V}{\omega L_s} \epsilon^{-\frac{\pi R_s}{4\omega L_s}} \tag{55}$$

It is obtained by applying a step function voltage to the series R_sL_sC circuit. The criterion for oscillations is

$$R_s < 2\sqrt{\frac{L_s}{C}} \tag{56}$$

where C is the capacitance of C_1 and C_2 in series. Many rectifier tubes have peak current ratings which must not be exceeded by such currents.

Currents shown in Table VII (p. 62) and Figs. 49 and 95 are reflected back into the a-c power supply line, except that alternate current waves are of reverse polarity. Small rectifiers have little effect on the power system, but large rectifiers may produce excessive interference in nearby telephone lines because of the large harmonic currents inherent in rectifier loads. High values of commutation reactance reduce these line current harmonics, but, since good regulation requires low commutation reactance, there is a limit to the control possible by this means. A-c line filters are used to attenuate the

line current harmonics. A large rectifier, with three-phase series resonant circuits designed to eliminate the eleventh, thirteenth, seventeenth, and nineteenth harmonics of a 60-cycle system, is shown in Fig. 96. Smaller rectifiers sometimes have filter sections such as those in Fig. 97; these are rarely used in large installations because of the excessive voltage regulation introduced by the line inductors.

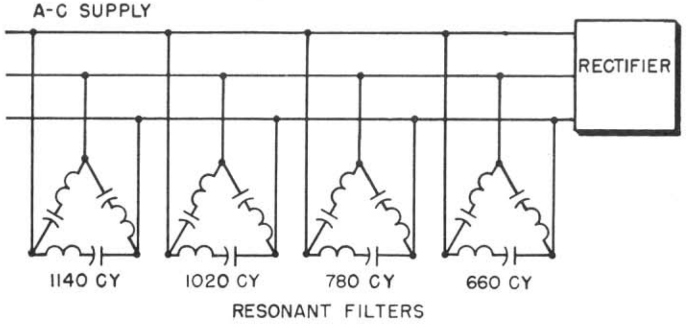


FIG. 96. A-c line filter for large power rectifier.

Filters designed to keep r-f currents out of the a-c lines are often used with high-voltage rectifiers. Even if the anode transformer has low radio influence, commutation may cause r-f currents to flow in the supply lines unless there is a filter.

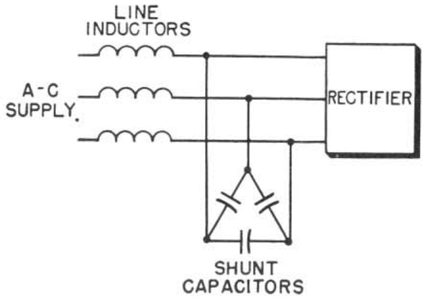


FIG. 97. A-c line filter for medium-sized power rectifier.

55. Rectifier Transients. The shunt-tuned filter currents mentioned in the preceding section are transient. Since the tube current is cut off during each cycle, a transient current may occur in each cycle. When power is first applied to the rectifier, another transient occurs, which may be smaller or larger than the cyclic transient, depending on the filter elements. In reactor-input filters the transient current can be approximated by the formula given in Section 54 for a step function applied to the series circuit comprising filter L and C plus R_s. This circuit is valid because the shunting effect of the load is slight in a well-proportioned filter. In capacitor-input filters, the same method can be used, but here the inductance is the leakage inductance of the anode transformer. Therefore, equation 55 applies, except that the maximum step function voltage is E_{pk}.

Transients which occur when power is first applied differ from cyclic transients in that they are spasmodic. Power may be applied at any instant of the alternating voltage cycle, and the suddenly impressed rectifier voltage ranges from zero to E_{pk}. Starting transients are difficult to observe on an oscilloscope because of their random character. It is necessary to start the rectifier several times for one observation of maximum amplitude, and the trace is faint because it appears for a very brief time.

Excessive current inrush, which occurs when a power transformer is connected to a supply line, plagues rectifier design. The phenomenon is associated with core saturation. For example, suppose that the core induction is at the top of the hysteresis loop in Fig. 18 (p. 24) at the instant when power is removed from the rectifier, and that it decreases to residual value B_r for $H = 0$. Suppose that the next application of power is at such a point in the voltage cycle that the normal induction would be B_m. This added to B_r requires a total induction far above saturation value; therefore heavy initial magnetizing current is drawn from the line, limited only by primary winding resistance and leakage inductance. This heavy current has a peaked wave form which may induce momentary high voltages by internal resonance in the secondary coils and damage the rectifier tubes. Or it may trip a-c overload relays. The problem is especially acute in large transformers with low regulation. A common remedy is to start the rectifier with external resistors in the primary circuit and short-circuit them a few cycles later. Some rectifiers are equipped with voltage regulators which reduce the primary voltage to a low value before restarting.

A-c line transients may cause trouble in three-phase rectifiers, especially those having balance coils, by shifting the floating neutral voltage. Filters like that in Fig. 97 prevent such transients from appearing in the rectified output.

In some applications the load is varied or removed periodically. Examples of this are keyed or modulated amplifiers. Transients occur when the load is applied (key down) or removed (key up), causing respectively a momentary drop or rise in plate voltage. If the load is a device which transmits intelligence, the variation in filter output voltage produced by these transients results in the following undesirable effects:

1. Modulation of the transmitted signal.
2. Frequency variation in oscillators, if they are connected to the same plate supply.
3. Greater tendency for key clicks, especially if the transient initial dip is sharp.
4. Loss of signal power.

A filter which attenuates ripple effectively is normally oscillatory; hence damping out the oscillations is not practicable. Nor would it remedy the transient dip in voltage, which may increase with non-oscillatory circuits. The filter capacitor next to the load should be large enough to keep the voltage dip reasonably small. An approximation for transient dip in load voltage which neglects the damping effect of load and series resistance is

$$\Delta E_D = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{57}$$

where ΔE_D is the transient dip expressed as a fraction of the steady-state voltage across R, and L, C, and R are as shown in Fig. 79(a). The accuracy of this approximation is poor for dips in transient voltage greater than 20 per cent.

Although the tendency for key clicks in the signal may be reduced by attention to the d-c supply filter elements, the clicks may not be entirely eliminated. Where key-click elimination is necessary, some sort of key-click filter is used, of which Fig. 98 is an example. This filter has inductance and capacitance enough to round off the top and back of a wave and eliminate sharp, click-producing corners. Figure 99 is an oscillogram showing a keyed wave shape with and without such a filter.

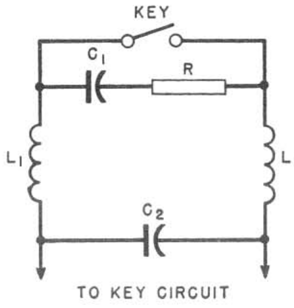


FIG. 98. Key-click filter.

In a choke-input filter, voltage surges are developed across the choke under the following conditions:

1. *Ripple Voltage.* With large rectifier commutation angles, or with grid-controlled rectifiers, a surge occurs once each ripple cycle. In the limit, this surge equals the rectifier peak voltage.

2. *Initial Starting Surge.* This surge adds to output d-c voltage. Under the worst conditions it raises the voltage at this point to twice normal and occurs every time rectifier plate voltage is applied.

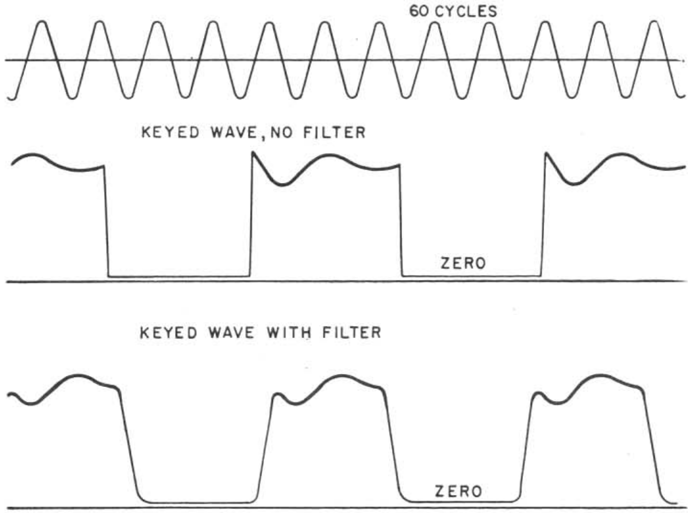


FIG. 99. Keyed wave shape with and without key-click filter.

3. *Keying or Modulation Transient.* Surge value depends upon constants L, C, and R_L, and is limited by considerations of wave shape. This occurs each time the key is opened or closed, or load is varied.

4. *Short-Circuit Surge.* If load R_L is suddenly short-circuited, it causes full d-c voltage to appear across the filter reactor until the circuit breaker opens. This occurs occasionally. Rectifiers are sometimes arranged so that, if the short circuit persists, the circuit breaker recloses 3 times and then remains open.

5. *Interruption of Reactor Current.* This surge voltage is limited only by losses and capacitance of the circuit, and it may be large, as shown by Fig. 73. Unless the reactor is designed to produce this voltage, it occurs only through accident.

Conceivably, surges 1, 2, and 3 may occur simultaneously and add arithmetically. A reactor insulated to withstand surges 1 plus 2 plus 3 also would withstand surge 4. A reasonable value of peak surge voltage comprising these factors is 2½ times the full d-c working voltage. If surges 1 and 5 are too much for reasonable insulation, the reactor is protected by a gap or other means.

If a rectifier is disconnected from the supply line while the load is off, interruption of plate transformer peak magnetizing current may cause high voltages to appear at random in the windings in much the same way as reactor current interruption causes high voltages. This is especially true if the transformer operates at high core induction. The effect is partly mitigated by the arc energy incident to the opening of the disconnecting switch. But unless the plate transformer is insulated specifically to prevent dangerously high voltages, protective elements may have to be added in a rectifier subject to switching at light loads. The necessity for such protection may be estimated from exciting volt-ampere data plus the curves of Fig. 73.

Insufficient attention sometimes is given to the manner in which power supply lines are brought into buildings. This is particularly important where a rectifier is supplied by overhead high-voltage lines. Because of their relatively high surge impedance, lightning and switching surges occurring on such lines may cause abnormally high voltages to appear in a rectifier and break down the insulation of transformers or other component parts. The likelihood of such surges occurring should be taken into account before the transformers are designed.

Underground cable power lines impose much less severe hazards: first because they are protected from lightning strokes, and second because they have much lower impedance (about one-tenth that of overhead lines). Surges on these cables have much lower values compared to those on overhead lines carrying the same rated voltage. Protection against these surges varies with the type of installation.

The best protection of all is provided by an indoor power system with an underground cable connecting it to the rectifier. Good protection is afforded by oil-insulated outdoor surge-proof distribution transformers, stepping down to the rectifier a-c power supply voltage, with an underground cable between the distribution transformer and rectifier. No protection at all is provided when overhead lines come directly into the rectifier building.

With the trend to dry-type insulation, it is desirable to use lightning arresters on overhead lines where they enter the building. Because of their low impulse ratio, dry-type transformers require additional arresters inside the building. When a line surge is discharged by a lightning arrester, there is no power interruption.

56. Rectifier Filter Charts. From the preceding sections, it can be seen that various properties of rectifier filters, such as ripple, regulation, and transients, may impose conflicting conditions on rectifier design. To save time in what otherwise would be a laborious cut-and-try process, charts are used. In Fig. 100 the more usual filter properties are presented on a single chart to assist in arriving at the best filter directly. This chart primarily satisfies ripple and regulation equations 46 and 53 for a choke-input filter.

Abscissa values of the right-hand scale are bleeder conductance in milliamperes per volt, and of the left-hand scale, filter capacitance in microfarads. Ordinates of the lower vertical scale are inductance in henrys. Lines representing various amounts of ripple in the load are plotted in quadrant I, labeled both in db and rms per cent ripple. In quadrant II, lines are drawn representing different types of rectifiers and supply line frequencies. A similar set of lines is shown in quadrant IV.

Two orthogonal sets of lines are drawn in quadrant III. Those sloping downward to the right represent resonant frequency of the filter L and C, and also load resistance R_L. The other set of lines is labeled $\sqrt{L/C}$, which may be regarded as the filter impedance. It can be shown that the transient properties of the filter are dependent upon the ratio of $\sqrt{L/C}$ to R_L.

The L scale requires a correction to compensate for the fact that ripple is not exactly a linear function of L but rather of $X_L - X_C$. The curves in the lower part of quadrant IV give the amount of correction to be added when the correction is greater than 1 per cent.

Instructions for Using Chart

1. Assume suitable value of bleeder resistance or bleeder current I_1 in millamperes per volt of E_{dc}. This is also steady-state peak ripple current in milliamperes.
2. Trace upward on assumed bleeder ordinate to intersect desired value of load ripple, and from here trace horizontally to the left to diagonal line for rectifier and supply frequency used. Directly under, read value of C.
3. Trace downward on same assumed bleeder ordinate to intersect diagonal line below for rectifier and supply frequency, and read value of L.
4. From desired ripple value, determine correction for L on graph at lower right, and add indicated correction to value of L.
5. Using corrected value of L and next standard value of C, find intersection in third quadrant, and read maximum resonant frequency f_r.

6. Using same values of L and C as in 5, read value of ratio $\sqrt{L/C}$.
7. Under intersection of $\sqrt{L/C}$ with load resistance R_L read values of the four transients illustrated in Fig. 101 (in per cent).

Example (shown dotted). Three-phase full-wave 60-cycle rectifier; $E_{dc} =$ 3,000 v; $I_2 = 1$ amp; $I_1 = 96$ ma; load ripple $= -50$ db; balanced line.
Solution:

Bleeder ma/volt = 0.032.
$C = 4.5\ \mu f$ (use $5\ \mu f$).
Scale value of $L = 0.78$ h; corrected value = 0.82 h.
Resonant frequency = 75 cycles.
Load resistance $R_L = 3{,}000$ ohms.
$i_m = 7I_2 = 7$ amp; $\Delta E_D = 12$ per cent; $\Delta E_R = 15$ per cent; $\Delta E_s = 80$ per cent.

In polyphase rectifiers the possibility exists of enough phase unbalance to impress a voltage on the filter having a frequency lower than the normal fundamental ripple frequency. If the filter L and C resonate near the unbalance frequency, then excessive ripple may be expected. Conversely, the L and C should have a resonant frequency lower than the unbalance frequency to avoid this trouble. Quadrant III of the chart has a series of lines labeled f_r, and the intersection of L and C thereon indicates this resonant frequency. It should be no higher than the value given in the small table on the chart if excessive ripple is to be avoided. This table is based on 2 per cent maximum unbalance in the phase voltages.

For most practical rectifier filters, transient conditions fall within the left-hand portion of the third quadrant. The other conditions sometimes help in the solution of problems in which L and C are incidental, e.g., the leakage inductance and distributed capacitance of a plate transformer.

Although the chart applies directly to single-stage, untuned filters with constant choke inductance, it can be used for other types with modifications:

(*a*) *Shunt-Tuned Choke per Fig. 93.* Figure 100 can be used directly for capacitance C, but, for a given amount of ripple, divide the chart values of inductance by 3 in order to obtain the actual henrys needed in the choke.

(*b*) *Swinging Choke.* If at light load the filter choke swings to S times the full-load value of henrys, multiply the capacitance obtained from the chart by the ratio S to find the capacitance needed (C_n). The

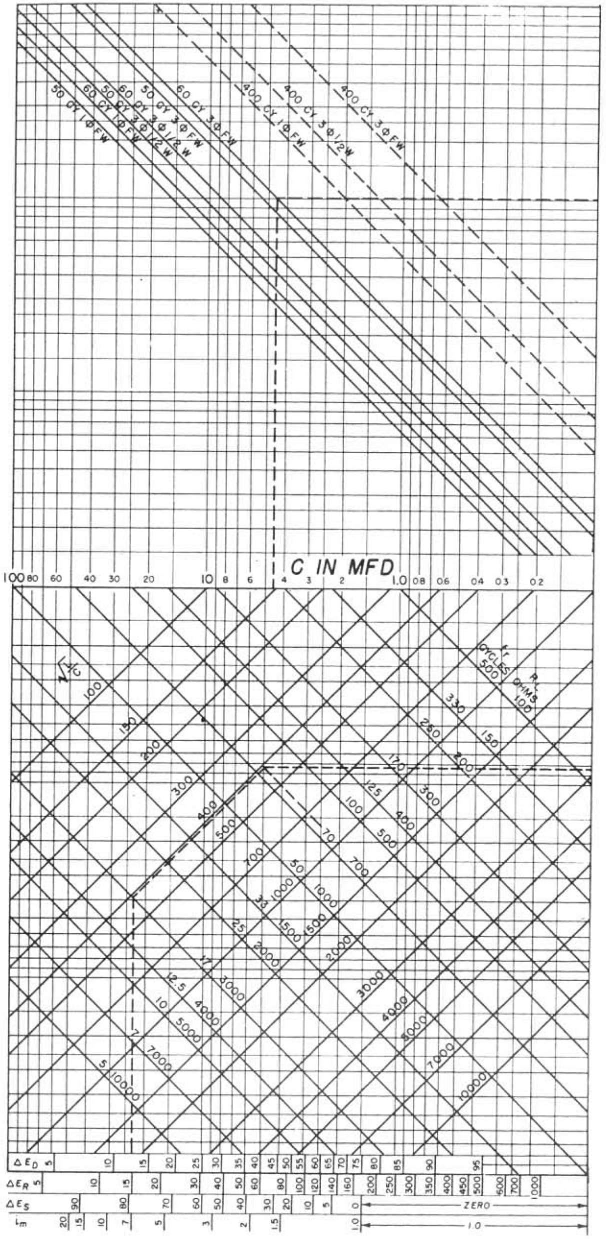
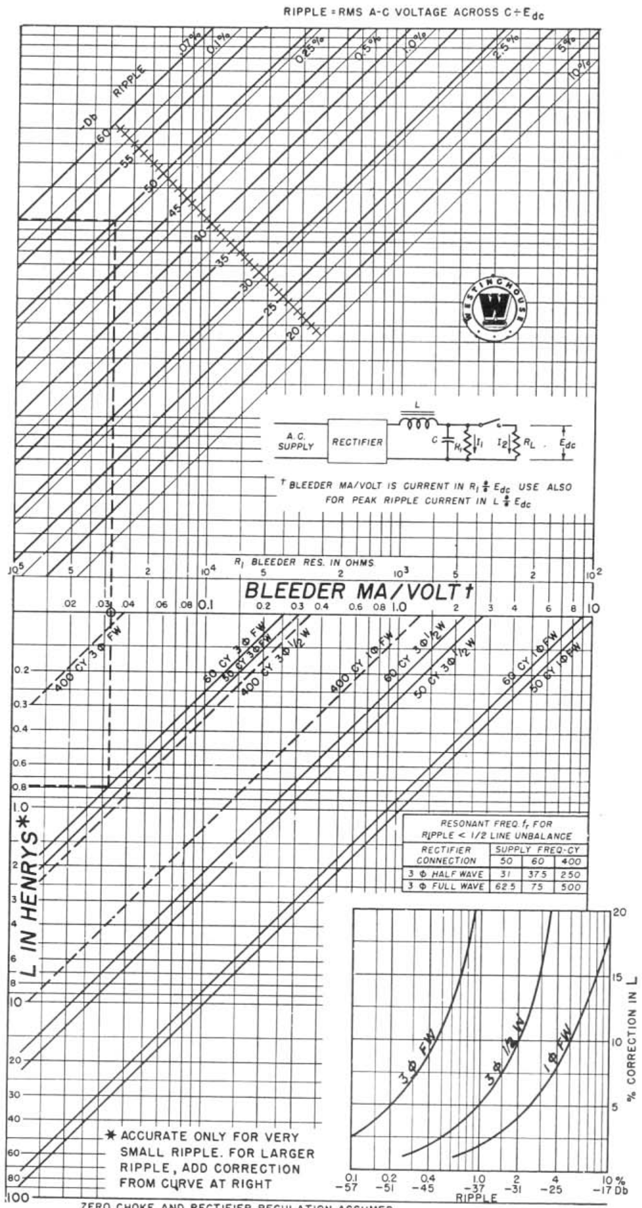


FIG. 100. Choke-input filter chart.



† BLEEDER MA/VOLT IS CURRENT IN $R_1 \div E_{dc}$ USE ALSO FOR PEAK RIPPLE CURRENT IN $L \div E_{dc}$

RESONANT FREQ. f_r FOR RIPPLE < 1/2 LINE UNBALANCE

RECTIFIER CONNECTION	SUPPLY FREQ-CY		
	50	60	400
3 Φ HALF WAVE	31	37.5	250
3 Φ FULL WAVE	62.5	75	500

* ACCURATE ONLY FOR VERY SMALL RIPPLE. FOR LARGER RIPPLE, ADD CORRECTION FROM CURVE AT RIGHT

ZERO CHOKE AND RECTIFIER REGULATION ASSUMED
L ASSUMED CONSTANT WITH VARYING DIRECT CURRENT

$$\text{Db RIPPLE} = 20 \log_{10} \frac{\text{RMS A-C VOLTAGE ACROSS C}}{0.707\, E_{dc}}$$

FIG. 100. *(Continued)*

value of L obtained by projecting the bleeder current downwards is the maximum or swinging value. It must be divided by S to obtain the full-load value. Transient conditions then may be approximated by using capacitance C_n and the full-load value of henrys.

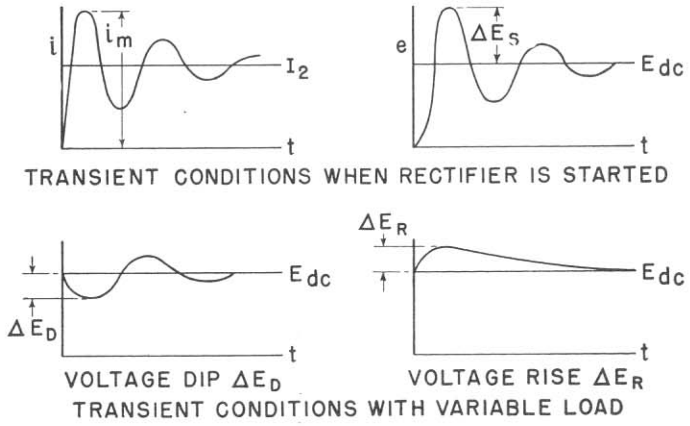


FIG. 101. Four transient conditions in choke-input filter circuit and curves.

(c) *Two-Stage Filters.* In a filter with two identical stages, Fig. 84(b), the chart can be used if it is recognized that the ripple is that on the load side of the first choke. For example, if the filter consists of two stages both equal to that in the example given for the single-stage filter, the ripple would not be -100 db but -75 db, because of the fact that the rectifier output has (per Table VII) only 4 per cent ripple, which is -25 db.

The regulation in a two-stage filter, as far as capacitor effect is concerned, depends upon the inductance of the first choke as in the single-stage filter. Therefore the chart applies directly to the inductance and capacitance of one stage. The peak ripple current likewise depends upon the inductance of the first choke, regardless of the location of the bleeder resistor. Transients, however, are more complicated, owing to the fact that the two stages interact under transient conditions.[1]

57. Rectifier Efficiency. Losses in a rectifier consist of transformer, tube, and filter losses. Filament power should be counted as loss, especially when a tube rectifier is compared with a rotating machine

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[1] See *Proc. I.R.E.*, *22*, 213 (February, 1934).

or metal disk rectifier. In spite of this loss, a high-voltage polyphase rectifier of the mercury-vapor or pool type may have 95 per cent efficiency at full load. In contrast, the rectifier for a radio receiver rarely has more than 60 per cent efficiency. Reasons for this low figure are the high tube and reactor IR drops and low transformer efficiency. The filament power, too, is a greater portion of the total.

58. Rectifier Tests. Even though the transformers, chokes, tubes, and capacitors have been tested before assembly of the rectifier, performance tests of the rectifier are desirable. These generally include tests of output, regulation, efficiency, ripple, and input kilovolt-amperes or power factor. Accurate meters should be used, and polyphase rectifiers should have balanced supply voltages. Wiring is tested at some voltage higher than normal, preferably with transformers, tubes, and capacitors disconnected to avoid damage during the test. Ordinary care in testing is sufficient except for regulation tests. If the regulation is low, the difference in meter readings at no load and full load may be inaccurate. Differential measurements are sometimes used, such as a voltmeter connected between the rectifier and a fixed source of the same polarity and voltage. Artificial loading of a high-voltage rectifier is often a problem. Water rheostats have been used for this purpose. Load tests, preferably in combination with the transmitter or other apparatus which the rectifier is to supply, are safeguards against field troubles. Operating tests are essential when the load is keyed or modulated, so that overheating or inadequate transformer operation may be detected.

Ripple is measured either with a special hum-measuring instrument or with a capacitance-resistance network arranged to block the direct current from the measuring circuit. Capacitance and resistance values in the measuring circuit should be so chosen as to avoid influencing the ripple or loading the rectifier transformer. Sometimes capacitance dividers are used for this purpose. The problem of proper values becomes particularly critical with high-voltage low-current rectifiers. The effect of stray capacitance is especially important.