

FILTER CIRCUITS

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PREFACE

Because of the inconsistency of data, and the difficulty of applying same to the practical problems confronting Radio Engineers and Amateurs in the building and selection of parts to form a consistent and effective filter, these data were formulated. It is the aim of the author to present all facts involved in the calculation and construction of filter circuits in a clear and concise way, and, so far as possible, in a non-technical way in order that those without technical training may follow it intelligently. This work is primarily intended to answer the question, "With what facts shall I start, and how shall I build a filter to serve my purpose?" It is designed to get at the underlying principals involved.

The author does not attempt to go into the field of application of filters to telephone work, for there it becomes very complicated and involved. The data given herein is applied only to radio work where smooth direct current is required from an alternating source.

The mathematics of these circuits may be applied to circuits of any magnitude so long as the voltage applied to the apparatus is regarded, and the parts selected accordingly.

Uses and Types of Filters.

Filters first became prominent with the development of the present complicated telephone system. By this means several messages can be sent over the same wire simultaneously, which is indeed advantageous to the telephone companies in view of the large saving in transmission facilities. The several messages are transmitted over the line, each at a different frequency. At the receiving end of the line the filters are so connected and tuned to pass currents of only one band of frequencies. In this way the several messages may be separated, each being directed to the proper telephone.

The Bell Telephone Company has probably carried on the most extensive research work in connection with filters of any company in the world, but their work was directed to their own interests, and is by far too complicated to be readable to the majority of technical men, to say nothing of amateur radio workers.

The development of the radio and the use of alternating currents as a power source has sent up a large cry for effective filter systems. Poor filtration of current used in this manner gives birth to a hum that may be of such magnitude as to completely overpower the signal being sent or received, and render it inaudible. Even if it does not reach this magnitude, a malicious hum will accompany the signal, rendering unbearable that which otherwise would be delightful and pleasing to the ear.

Filters may be classified in a number of ways. The most frequently used classification for radio work is high pass, low pass, and band pass filters. High and low pass filters, as the name indicates, are designed to pass currents of high and low frequencies respectively, stopping all others up to or from the required point, as the case may be, while band pass filters are designed to pass currents within a certain range or "band" of frequencies, excluding all others. It is with the latter type telephone companies are concerned. For filtration of current for power supplies for amateur work they may be classified as "brute-force" and "tuned trap" filters, the former being used most frequently in a "hit or miss" way, while the latter is by far the most desirable and economical. It is the purpose of this treatise to make an analysis of filters, using the latter classification, attempting to show the characteristics of each, and show the advantages of the "tuned trap" type filter.

Rectified Currents.

Practically the only source of power available to radio workers is alternating, this being almost universally used for house lighting. To adapt this to radio work calls for some form of transition from A.C. to D.C. This may be accomplished by means of a rectifier, but this alone is insufficient to make it adaptable

as can be readily seen from

Fig.1, an oscillogram of the voltage from a full wave rectifier. The current and voltage does not become negative, but becomes zero every half cycle, thus furnishing an A.C. component. It is for the purpose

of smoothing out this wave that filters are designed.

The fundamental frequency doubles in the process of rectification as can be seen by reference to Fig.1. It is to be expected then, that the major A.C. component of the current will occur at this frequency, and at the same time, as in the case of the unrectified current, all the harmonics will be present, but doubled in frequency.

The magnitude of the voltage can be calculated from the analytical expression for the wave, but the process is very laborious and little is to be gained from such an analysis. To give some idea as to the magnitude of the voltage to be encountered at the load for the different frequen-

—— Voltage
----- Current.

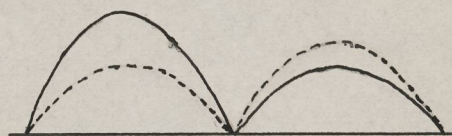


Fig. 1.

cies in comparison with the D.C. voltage, an experimental analysis made by Robt. S. Kruze, which appeared in the April 1929 issue of Radio Broadcast will be given.

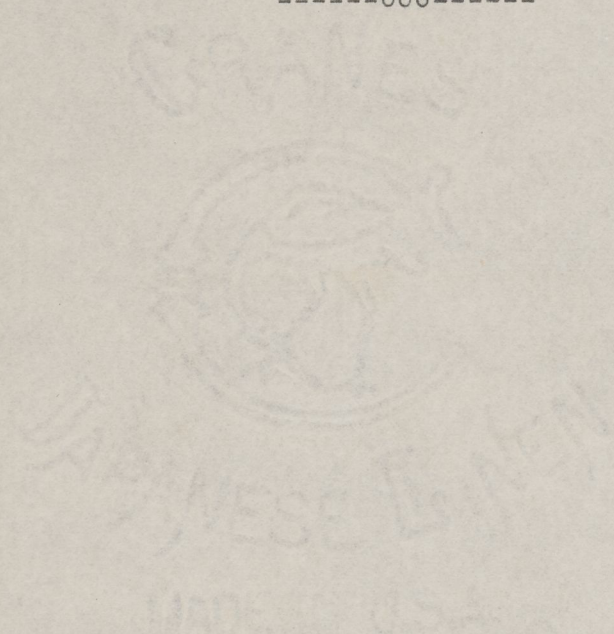
<u>Frequency</u>	<u>Voltage at load</u>
D.C.....	530.0
60.....	25.0
120.....	245.0
180.....	1.2
240.....	17.6
300.....	0.16
360.....	12.5
480.....	7.5
600.....	6.7
720.....	3.5
840.....	1.25
900.....	0.51

This analysis was made with an elaborate set-up by which the frequencies could be differentiated. It is interesting to note that the voltage at 120 cycles is approximately half that of the direct current voltage. A condition similar to this one may be expected in the case of any rectified current.

The ideal filter section would be one by which all the alternating component of the rectifier current would be suppressed with no accompanying loss of D.C. potential. As the A.C. component is attenuated, though, the loss of D.C.

potential increases due to an increase in the resistance of the circuit. The problem, then, is to secure maximum attenuation with a minimum loss of D. C. postential, at the same time keeping the cost of such a filter within an economic range.

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"Brute Force" Filters.

"Brute force" filters are probably the most frequently used type of filter by amateurs. This condition arises from inconsistent data with regard to such circuits and the inapplicability of same to the problems arising in the construction of filters. It is only by "Brute force" that the attenuation factor is decreased, and at the same time a great potential drop is experienced due to the excessive resistance of the choke necessary for such a circuit. This, of course, is of no consequence in small, low potential circuits, but becomes extreme importance as the voltage of the circuit is increased, for this means a large potential drop across the choke coil.

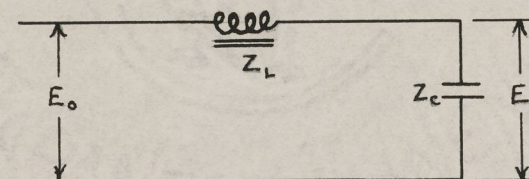


Fig 2.

To determine the characteristics of a "brute force" filter, the above arrangement of one iron core reactance and one capacity shall be considered. In this consideration, the resistance of the load is assumed to be extremely large and the reactance is assumed to have no resistance. The voltage, E_o , is the vector sum of the potential drop across the choke and the potential drop across the capacity, or

$$E_o = Z_L I - Z_C I \quad (1)$$

as E_L and E_C are at 180° phase relations, and the drop of potential across the capacity is

$$E = -Z_C I \quad (2)$$

Deviding equation (2) by (1)

$$\frac{E_o}{E} = \frac{Z_c I}{Z_c I - Z_L I} \quad (3)$$

$$\text{or } E_o = E \frac{Z_c}{Z_c - Z_L}$$

In this equation, the fraction $Z_c / Z_c - Z_L$ is the attenuation factor of the filter.

In the above derivation, $Z_L = X_L$ and $Z_c = X_c$. A careful inspection of the equation reveals that when the inductance $L=0$ consequently $Z_L=0$, making the attenuation factor unity regardless of the capacity used. When $L=\infty$, then $Z_L=\infty$ thus causing the attenuation factor to become infinitesimal. Applying the same reasoning to the capacity, when $C=0$, then $Z_c=\infty$ and the attenuation factor approaches one, but when $C=\infty$ then $Z_c=0$, and the attenuation factor becomes zero.

As $X = 2\pi fL$ and $X_c = \frac{10^6}{2\pi fC}$ it can be seen from the foregoing discussion that as the frequency is increased, the filtering effect will increase. Thus one is safe in assuming that when the maximum economical filtration is designed for the fundamental frequency, the components of the other frequencies are suppressed to insignificance.

The practice for commercial filters of this type is to use a 30 henry choke in conjunction with the proper size condenser. Fig.(3) gives the variation of the attenuation factor for various capacities the inductance being fixed at 30 henries.

The commercial type filter is usually made up of one choke and two condensers or two chokes and three condensers, the condensers being shunted across the line between the chokes.

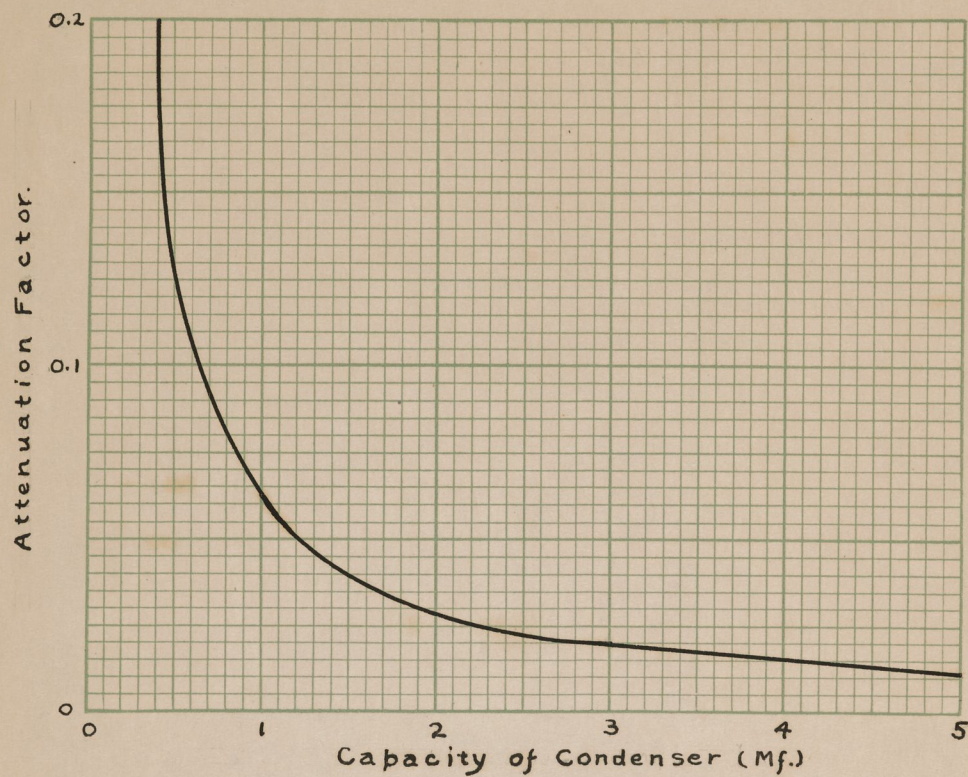


FIG. NO. 3

TITLE:- Variation of Attenuation Factor.
Inductance Constant. (30 Henries.)

INTERPRETATION OF CURVES

It has been shown that the choke in conjunction with the condenser shunted across the line on the load side forms of the filter network, and the manner in which it operates has been discussed. Next let me consider the first capacity and its functions in conjunction with the filter section.

The electromotive force applied to the filter is of complex wave form, and may be expressed analytically by the following formula.

$$C = \frac{2}{\pi} E_1 - \frac{4}{3\pi} \times E_2 \cos 2\omega t - \frac{4}{15\pi} E_3 \cos 4\omega t - -$$

Where E is equal to the maximum value of the voltage and $\omega = 2\pi f$. The current through the first condenser will then be a complex wave which may be expressed for a full wave rectifier thus:-

$$i = .72I \sin \omega t + .34I \sin (2\omega t + 24) + .09I \sin (3\omega t + 77) \\ + .06I \sin (4\omega t - 31) + .034I \sin 5\omega t - - - -$$

The above equation was taken from the work of Clyde Farrar on filter circuits (see bibliography).

The function of the first condenser is to store energy during that part of the cycle when the rectifier is passing current and to give up its store of energy during that period when the current from the rectifier is zero, the assumption being that the filter will keep constant current during the time in which the rectifier is passing current. We are then interested only in current through the first condenser during the discharge period. From the equation for the discharge of a condenser, the proper size to maintain constant, or nearly constant current may be obtained. That equation is -

$$i = \frac{E}{R} e^{-\frac{t}{RC}}$$

where R is the resistance of the load, E the applied voltage and C the capacity of the condenser. For i to remain sensibly constant

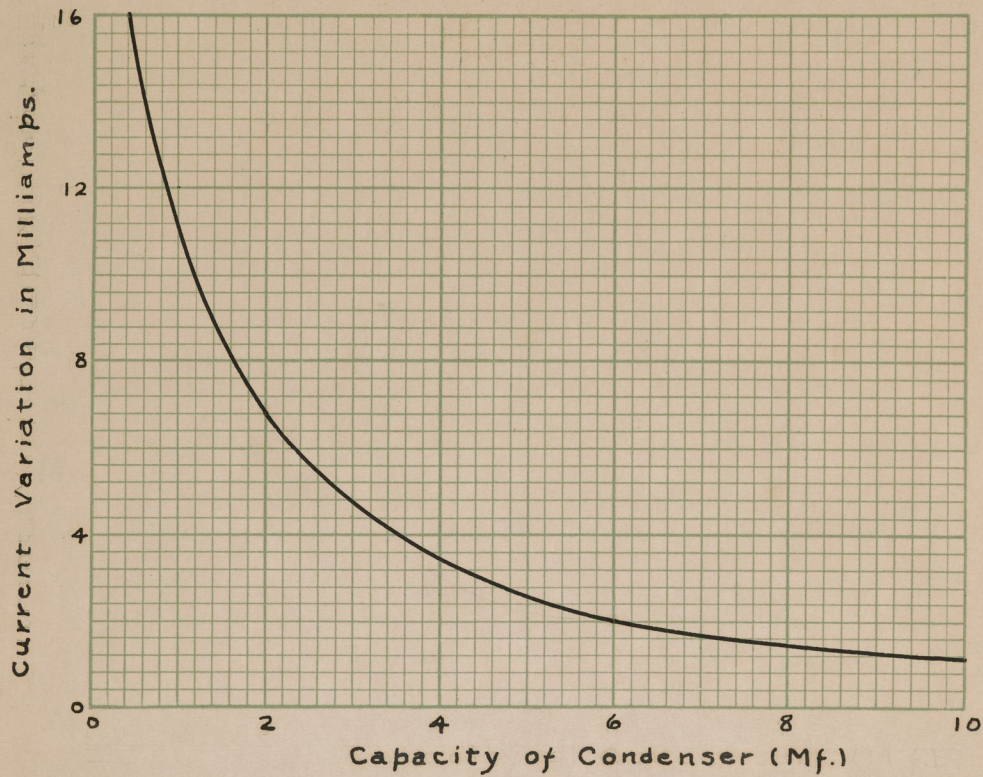
$$e^{-\frac{t}{RC}}$$

Must be as near one as possible at all times. To accomplish this, the product RC must be large, as t is approx. 1/4 cycle.

The initial discharge current for the condenser is fixed by the load and not the size of condenser, therefore the initial condenser current is independent of the capacity. With a fixed applied voltage and a fixed load resistance, varying C only varies the exponent of e , and has no effect on the discharge current except to maintain the current more nearly constant during discharge. Assuming to have a constant value of 0.004 sec. Fig.(4) shows the effect of adding capacity. From this curve it is easily seen that capacities over 4 mf. improves conditions, but slightly.

Before leaving the subject of "brute force" filters, a few comments shall be made. The economic value of the first capacity, from the foregoing discussion was shown to be something around 4 mf. Capacities above this point are by all means usable, but the advantage of large ones are not sufficient to justify the additional cost in obtaining them.

As has been stated, the commercial practice is to use 30 henry chokes in filter design. In the selection of a condenser to work in conjunction with this choke to form the filter network, it must be remembered that $X_c = \frac{10^6}{2\pi fC}$ or that the inductance decreases as the capacity of the con-

FIG. NO. 4.

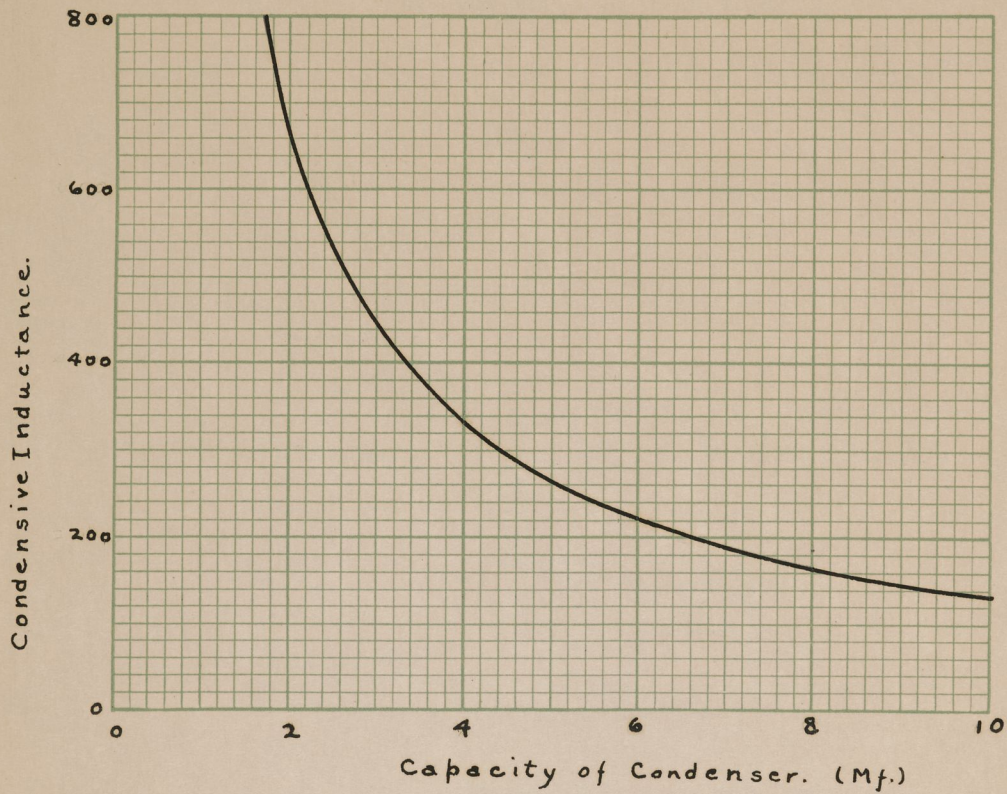
TITLE:- Current Change for Constant Discharge
Time. (0.004 seconds.)

INTERPRETATION OF CURVES

denser is increased. To reduce the attenuation factor, it is essential to reduce X_c to a minimum. Again we are confronted with the problem of economics. Fig. (5) shows the variation of X_c with given changes in the capacity, which is the graphic representation of the equation given above. From this it is seen that capacity of the condenser has reached its economical limit at about 3 to 4 microfarads.

Further attenuation is accomplished by the addition of other filter sections, as the efficiency of a single section has reached its economic maximum at the points stated above. It should be kept in mind that the attenuation factors vary in geometrical progressions with the number of sections.

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FIG. NO. 5TITLE: Variation of X_c with C .

INTERPRETATION OF CURVES

"Tuned Trap" Filters.

"Brute force" filters perform their work well and are very serviceable, but have some disagreeable traits. They are large, heavy, and the chokes must necessarily have a fairly high resistance to keep their size from being prohibitive. This last factor will usher in the problem of excessive voltage drop. It is the aim of the author to show what can be accomplished with small capacities and chokes in the way of filtration by arrangement into a "tuned trap." This type of filter is becoming more and more popular for radio work because of its economy.

The tuned filter or "trap" consists of an induction coil and a condenser connected in parallel, and inserted in one side of the line. The induction coil furnishes the pass for the direct current while both form a pass for the A.C. The trap, however, is tuned to the desired frequency, and by resonance will offer a high resistance to that component of the current.

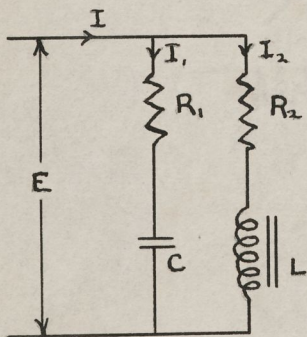


Fig. 6

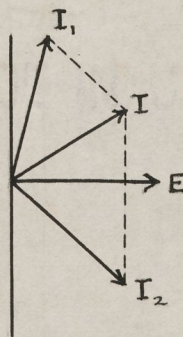


Fig. 7.

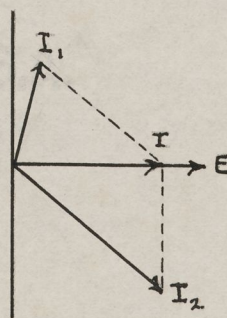


Fig. 8.

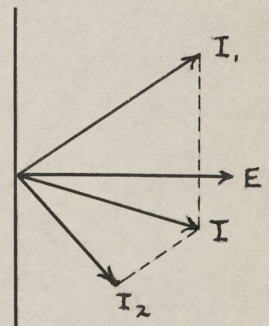


Fig 9.

Figure (7) is the vector diagram for the current above the resonant frequency. In this case the current leads the voltage, the simplified circuit being one containing a condenser and a resistance in series. Fig. (8) is the vector diagram for resonant frequency, the voltage and current being in phase, and the equivalent circuit being pure resistance. Fig. (9) represents the conditions when the impressed frequency is below the resonant value. The current in this case lags behind the voltage, and the equivalent circuit would be one containing a resistance, and inductance in series.

From Fig.(6)

$$Z_1 = R_L + j\omega L$$

$$Z_2 = R_C - j \frac{1}{\omega C}$$

$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{R_L + j\omega L} + \frac{1}{R_C - j \frac{1}{\omega C}}$$

$$\begin{aligned} &= \frac{(R_C - j \frac{1}{\omega C}) + (R_L + j\omega L)}{(R_L + j\omega L)(R_C - j \frac{1}{\omega C})} \\ \text{Then } Z &= \frac{(R_L + j\omega L)(R_C - j \frac{1}{\omega C})}{(R_L + j\omega L)(R_C - j \frac{1}{\omega C})} \end{aligned}$$

Rationalizing and collecting terms:

$$Z = \frac{R_C(R_L^2 + \omega^2 L^2) + R_L(R_C^2 + (\frac{1}{\omega C})^2) + j(\omega L(R_C^2 + (\frac{1}{\omega C})^2) - \frac{1}{\omega C}(R_L^2 + \omega^2 L^2))}{(R_L + R_C)^2 + (\omega L - \frac{1}{\omega C})^2}$$

$$= \frac{(R_c R_L (R_c + R_L) + R_c \omega L^2 + R_L \left(\frac{1}{\omega C}\right)^2) + j \left[R_c^2 \omega L - R_L^2 \frac{1}{\omega C} - \frac{L}{C} \left(\omega L - \frac{1}{\omega C} \right) \right]}{(R_L + R_c)^2 + \left(\omega L - \frac{1}{\omega C} \right)^2}$$

Dividing this expression into its two components, letting R^1 equal effective resistance and L^1 equal the effective reactance, we have

$$R' = \frac{(R_c R_L (R_c + R_L) + R_c (\omega L)^2 + R_L \left(\frac{1}{\omega C}\right)^2)}{(R_L + R_c)^2 + \left(\omega L - \frac{1}{\omega C} \right)^2}$$

$$\text{and } L' = \frac{(R_c^2 \omega L - R_L^2 \frac{1}{\omega C} - \frac{L}{C} \left(\omega L - \frac{1}{\omega C} \right))}{(R_L + R_c)^2 + \left(\omega L - \frac{1}{\omega C} \right)^2}$$

In case the resistance of the inductive branch is large as compared to that of the condensive branch, the above equation may be simplified to the following approximately correct terms.

$$R' = \frac{R}{m^2 R^2 \frac{C}{L} + (m^2 - 1)^2} \quad (1)$$

$$L' = \frac{R^2 \frac{C}{L} + (m^2 - 1)}{m^2 R^2 \frac{C}{L} + (m^2 - 1)^2} \quad (2)$$

When R = Total actual resistance of the circuit.

C = Actual capacity in farads.

L = Actual Inductance.

$$m = 2 \pi f \sqrt{C L}$$

The above equations (1) and (2) will be referred to later.

It will be remembered that resonance occurs when $X_L = X_C$; that is when

$$2 \pi f L = \frac{1}{2 \pi f C}$$

From this equation

$$L = \frac{1}{(2 \pi f)^2 C}$$

Figure (10) shows this relationship calculated for the fundamental frequency of 120 cycles.

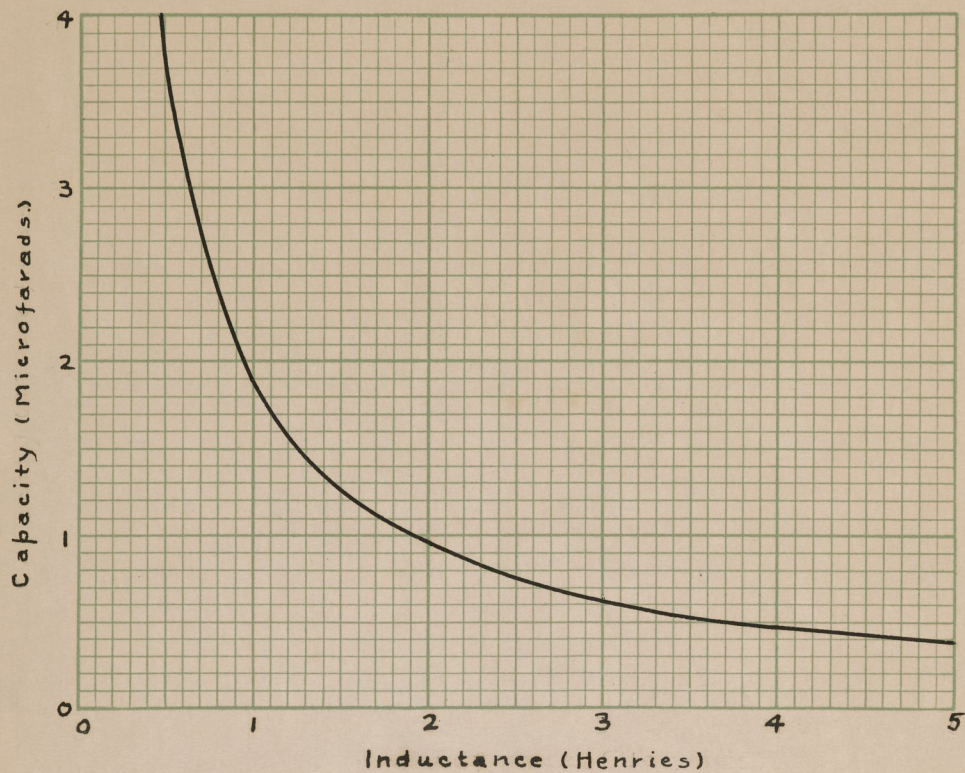
Referring to equation (2) it is seen that for resonance $m = 1$ and L' is thus equal to L , which reduces to zero. The effective resistance, however, as resonance is approached, becomes large and is seen to increase with the decrease of the actual resistance of the circuit. From this can be seen the importance of reducing the circuit resistance as low as is economically possible.

The effect of shunting a condenser across the line side of the filter section and the economical size of such a condenser has already been discussed in the previous chapter. With this discussion in mind, a 3 to 4 microfarad condenser may be shunted across the line side. Likewise a 3 to 4 microfarad condenser is found to be of intrinsic value on the load side of the filter.

The tuned trap with a condenser shunter across the

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FIG. NO. 10

TITLE: C and L To Produce Resonance At 120 Cycles.

INTERPRETATION OF CURVES

line on either side of it will attenuate the alternating component sufficiently for radio work except in extreme cases where some harmonic assumes an important place. In this case a second tuned trap must necessarily be added. Conditions of this kind are very rare, however.

It can be seen from the foregoing discussion that a filter of the "tuned trap" type can be constructed very cheaply, its chief advantage being compactness, reduction of weight and high efficiency. By use of the small choke or chokes, the actual resistance of the unit is reduced to practically nothing, while the attenuating effect mounts high. A filter of this type eliminates bad voltage drops so often experienced by radio workers.

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Filter Chokes

The question of the design of filter chokes, while of great importance to the radio industry, is very involved. It is thought advisable, however, to summarize the essential facts brought out in the work of C. R. Hanna, T. Spooner, Herbert F. Wareing and others. (See Bibliography)

The filter choke differs from the ordinary reactance in that it must be designed to carry, we might say, two currents, i.e. a direct current and a super-imposed alternating current. This gives rise to new terms to be reconed with.

Permeability is defined by the equation.

$$\mu = \frac{B}{H}$$

For a coil carrying both A.C. and D.C., a new permeability is introduced known as incremental permeability. When the direct current passes through the choke, the flux density rises to a certain point on the permeability curve. At this point the alternating component causes the flux to describe a small hysteresis loop. This is not the permeability (μ) but a smaller value ($\mu\Delta$) which is equal to the slope of the line drawn through the tips of the loop. As H due to the D.C. increases, the hysteresis loop moves up and the value ($\mu\Delta$) becomes smaller. The method of obtaining ($\mu\Delta$) can be found in a paper by T. Spooner published in the A. I. E. E. Journal of Jan. 1929, Fig. (11) and Fig. (12) gives permeability and incremental permeability respectively.

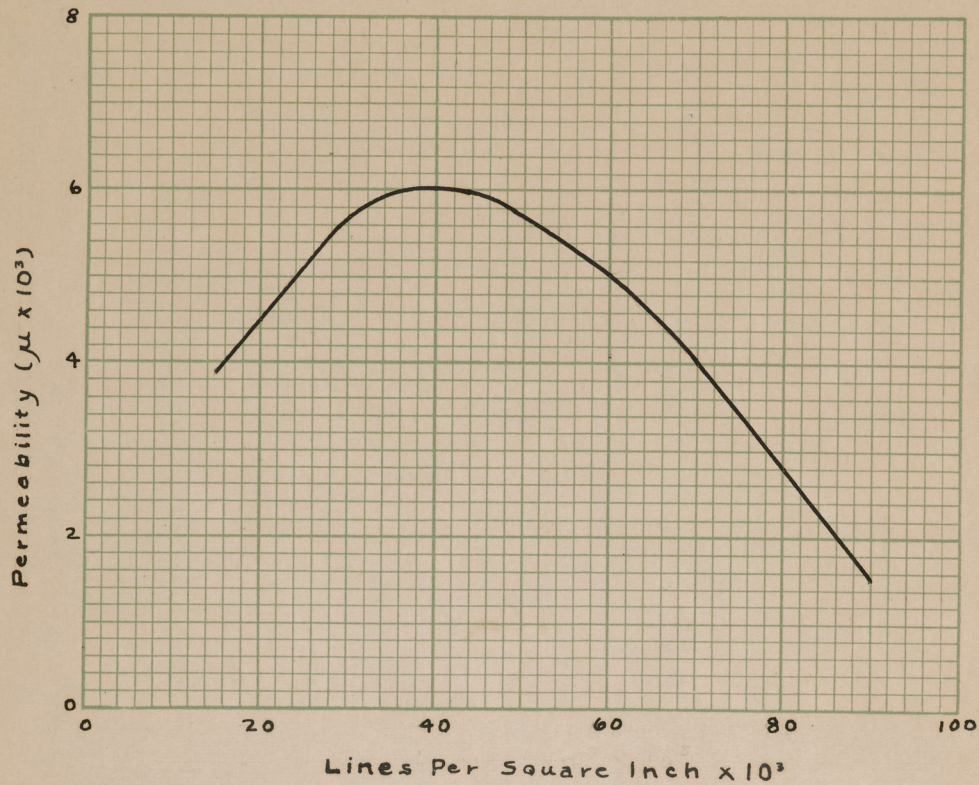
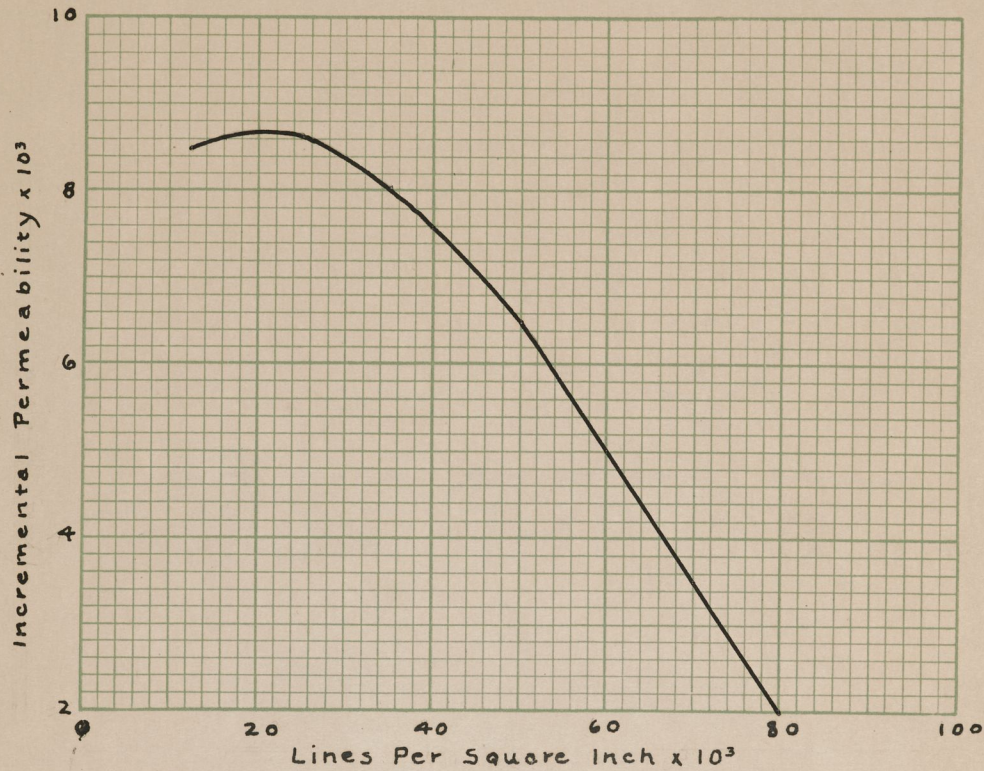


FIG. NO. 11.

TITLE: Permeability Curve for Westinghouse "MA" Steel.

INTERPRETATION OF CURVES

FIG. NO. 12

TITLE: Incremental Permeability Curve for
Westinghouse "MA" Steel.

INTERPRETATION OF CURVES

Both the permeability and incremental permeability curves were made use of by Hanna in preparing his design chart for reactances carrying D.C. with a superimposed alternating current. Hanna's method was as follows:

Using the following notations:-

B = Steady flux density in iron and air gap expressed in gaussses.

N = Number of turns in winding.

I = Direct current in Amperes.

A = Area of core section and air gap in cm².

l = length of iron path in cm.

L = A.C. inductance in henries.

μ = Normal permeability = $\frac{B}{H}$

μA = Incremental permeability = $\frac{\Delta B}{\Delta H}$

We have

$$B = \frac{0.4 \pi N I}{\frac{l}{\mu} + a} \quad (1)$$

$$\text{and } L = \frac{0.4 \pi N^2 A \times 10^{-8}}{\frac{l}{\mu A} + a} \quad (2)$$

from (1)

$$N = \frac{B (\frac{l}{\mu} + a)}{0.4 \pi I} \quad (3)$$

Substituting in (2)

$$\begin{aligned} L &= \frac{B^2 (\frac{l}{\mu} + a)^2 A \times 10^{-8}}{0.4 \pi I^2 (\frac{l}{\mu A} + \frac{a}{1})} \\ &= \frac{B^2 (\frac{l}{\mu} + \frac{a}{1})^2 1 A \times 10^{-8}}{0.4 \pi I^2 (\frac{l}{\mu A} + \frac{a}{1})} \quad (4) \end{aligned}$$

Letting $l_A = V$, the volume of iron in the case,

$$\frac{LI}{V} = \frac{B \left(\frac{1}{\mu} + \frac{a}{l} \right)^2 \times 10^{-8}}{0.4\pi \left(\frac{1}{\mu\Delta} + \frac{a}{l} \right)} \quad (5)$$

Also from (1)

$$\frac{NI}{l} = \frac{B}{0.4\pi} \left(\frac{1}{\mu} + \frac{a}{l} \right) \quad (6)$$

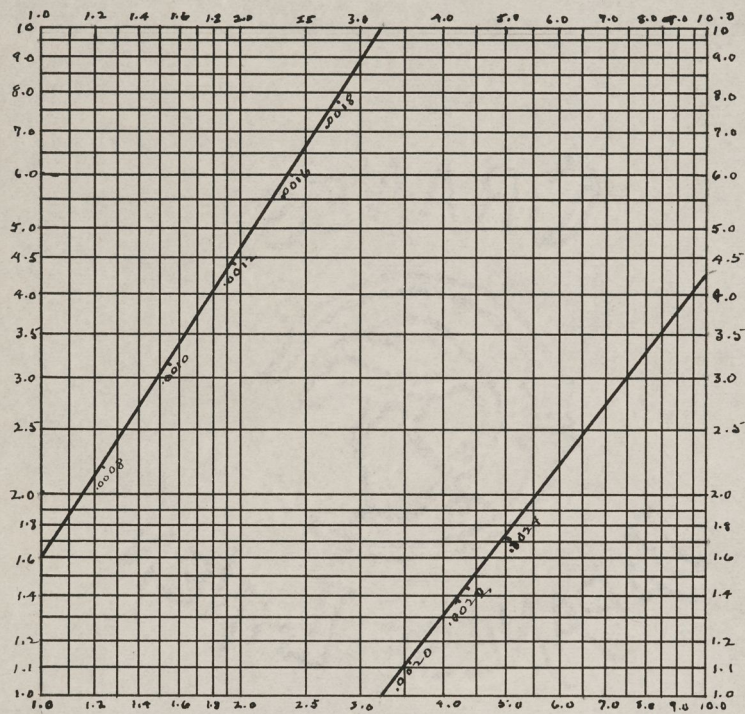
For any assigned value of $\frac{a}{l}$ (the per cent. air - gap) equations (5) and (6) may be considered as parametric equations with B as the parameter, and a curve of $\frac{LI}{V}$ against $\frac{NI}{l}$ can be plotted. To do this, several values of B are assigned, and the value of μ and $\mu\Delta$ corresponding to B obtained from the curves of Fig.(11) and (12). These values are substituted in equations (5) and (6) to determine corresponding values of $\frac{LI}{V}$ and $\frac{NI}{l}$. $\frac{NI}{l}$ represents the steady ampere turns for each centimeter of iron length, and $\frac{LI}{V}$ is a quantity, which if divided by the square of the current gives the inductance per cm. of the core. Fig.(13) is Hanna's design chart.

The above chart is used in the following way, the desired inductance L and the direct current I being known:

1. It will now be necessary to assume some core size, and the height for the stack of laminations. Then determine the area of the core A and the length of the magnetic path? $V = Al$

2. Compute $\frac{LI}{V}$

3. From the design chart, find the value of $\frac{NI}{l}$



DESIGN CHART

For Iron-Core Chokes Carrying
Both A.C. and D.C.
Westinghouse "M.A." Steel.

Fig. 13.

corresponding to the above value of $\frac{LI^2}{V}$.

4. The total number of turns to be used is then found by dividing the above value of $\frac{NI}{I}$ by I and multiplying by 1.

5. The approximate length of air gap determined by noting the $(\frac{a}{I})$ number nearest the point on the curve used in getting $\frac{NI}{I}$. This number is multiplied by 1 to get a.

6. If it is now found that the proper number of turns cannot be gotten in the winding space, or that the space is unnecessarily large another assumption must be made for d and the design followed through again.

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CONCLUSIONS

From the foregoing discussions we may say that the most effective "brute force" filter circuit may be constructed using a 30 henry choke with ~~ta~~ three or four microfarad condensers shunted on either side of it. As has been pointed out, this will form the most effective filter for the most nominal cost of constructing same. If further attenuation is desired it can be obtained more economically by the addition of another filter network consisting of a 30 henry choke and a three to four microfarad condenser.

It has been pointed out that resonance can be produced for the principle frequency (120 cycle) by any number of sizes of chokes connected in parallel so long as they are balanced. Selecting a 1.2 henry choke as an example, we find by calculation the accompanying condenser should be somewhere near 1.5 microfarads to produce resonance at 120 cycles. Therefore, an effective filter may be constructed using a 1.2 henry choke in parallel with a 1.5 microfarad condenser connected in one side of the line, and a three to four microfarad condenser shunted across the line on either side of the above trap.

In either of the above cases the current the network is to carry should be taken into consideration, otherwise undue heating may occur.

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APPROVAL.

The foregoing thesis is hereby approved as a creditable study of engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this aproval the undersigned does not necessarily endorse or approve any statement, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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