Transformer Design Data
High-Frequency, Powdered-Core Inductor

A. Permeability:

"Intrinsic permeability" is the permeability of the magnetic particles.

"Composite permeability," "ring-core permeability," or just "permeability" describe the permeability of a core-formed in a ring and wound with a coil.

The relationship between ring-core permeability and intrinsic permeability is given by:

$$u = (ui)^p \qquad (1)$$

u=ring-core permeability

ui=intrinsic permeability

p="packing factor" or fraction of the core volume occupied by magnetic material

"Effective permeability" is used to describe the permeability of a cylindrical or slug-type core. It is much lower than ring core permeability of the same demagnetizing effects at the ends of the cylinder.

(See chart on page 3-51)

B. Inductance:

The inductance of a toroidal coil on a ring core is given by:

$$L = \frac{4N^2}{d}\left[A' + A(u-1)\right] X\ 10^{-9} \text{henry} \qquad (2)$$

N=number of turns of coil

d=mean diameter of core in cm.

A'=mean cross section of the coil at right angles to the flux path in cm^2

A=cross-section of core in cm^2

u=ring-core permeability of the coils

The inductance of a coil on a cylindrical, or slug-type core, if the coil is the same length as the core, is:

$$L = Lo\left[1 + \left(\frac{bi}{bo}\right)^2 (Ue-1)\right] \qquad (3)$$

ho = inductance of coil without iron

bi = radius of iron core

bo = mean radius of the coil

Ue = effective permeability (Table 2-35)

If the core is longer than the coil, the effective permeability is increased to a value:

$$Ue^{\circ} = Ue\sqrt[3]{\frac{li}{lo}}$$

li = length of core

10 = length of coil

C. Core-Loss and Q

Core loss is of interest in high-frequency inductors primarily because of its effect on Q, or quantity factor.

The addition of the core increases not only inductance but also resistance.

The increase of resistance of a toroidal coil on a ring core d due to core loss is:

$$R = \left[(aBm + c)f + ef^2\right]uh \text{ ohms}$$

R = resistance added to coil by core

a = hystersis loss coefficient

c = residual loss coefficient

f = frequency Hz

Bm = peak a-c flux density in gausses

u = ring-core permeability

h = inductance of the coil with the core in henries

The resistance added to a coil by a cylindrical core:

$$R = lc\frac{4\pi^{2} ue^{2} bi^{2} lip}{bc^{2}\sqrt{4bc^{2} + lc^{2}}} \text{ ohms} \qquad (6)$$

Refer to equations 3 & 4 for symbol meanings.

p = loss factor of core material

The loss factor must be determined by measurements upon a sample of the particular core material.

D. Permeability Tuning:

"Permeability tuning" or "variable reluctance tuning" is the system of adjusting a circuit to resonance at a desired frequency by moving an iron core in or out of the coil.

Such a system is ideal for a circuit tuned to some fixed frequency, such as an intermediate-frequency transformer circuit.

E. Incremental permeability tuning:

Incremental permeability tuning is a system of adjusting the resonant frequency of a circuit by varying the permeability of the iron core without any mechanical motion.

The permeability is varied by means of a-c magnetization on the same principle as the saturable reactor.

Increase of a-c magnetization causes a decrease of inductance and and an increase of frequency.

By proper design, the increase of frequency from some minimum value may be made proportional to the direct current.

A. Capacitance Formula:

The general expression for the capacitance of a multiplate capacitor is

$$C = .0885K \frac{(N-1)S}{T} \quad (1)$$

S = area in square cm. of a moving plate overlapping a fixed plate.

T = separation of plates in cm.

K = dielectric constant

N = total number of similar plates (at ternate plates being connected in parallel.)

B. Impregnated Paper Capacitors

Construction: In the roll construction the resultant capacitance is twice that obtained with a parallel-plate construction since both sides of the foil are active.

The extended foil construction gives the lowest value of self-inductance since all ~~turns~~ are bonded together; the construction approaches that of a stacked parallel plate capacitor.

Temperature: Increasing the ambient temperature above 40 degrees centigrade requires voltage derating for an equivalent life expectancy at the high temperatures, and that the derating factors are a function of capacitor size.

Capacitor size can best be evaluated for d-c ratings in terms of energy content in watt-seconds.

$$\text{Watt-second} = \tfrac{1}{2}CE^2$$

C = capacitance in microfarads

E = d-c voltage in kilovolts.

Generally speaking, the life expectancy of a capacitor without derating is halved for each 10 degree cent. rise in temperature.

A. Audio Transformers

Primary inductance must be high, leakage inductance and distributed and other capacitancies must be low.

The equivalent network of an inequality ratio transformer may be referred to either the primary or secondary circuit, provided the correct transformations are made.

To reflect the secondary constants to the primary, it is necessary to multiply all the impedances on the secondary side by the ratio: L_1/L_2.

With iron-core transformers, the ratio L_1/L_2 is for all practical purposes equal to the square of the turns ratio.

Voltages are transformed by the turns ratio, currents by the inverse of the turns ratio.

If Np = primary turns, and N_2 = secondary turns, the secondary constants referred to the primary, are:

$$L_2' = \left(\frac{Np}{Ns}\right)^2 L_2 \qquad r_2' = \left(\frac{Np}{Ns}\right)^2 r_2$$

$$E_2' = \left(\frac{Np}{Ns}\right) E_2 \qquad I_2' = \left(\frac{Ns}{Np}\right) I_2 \qquad (1)$$

$$C_2' = \left(\frac{Ns}{Np}\right)^2 C_2$$

$$rL' = \left(\frac{Np}{Ns}\right)^2 rl$$

After these conversions are made, the transformer becomes a unity-ratio transformer and can be replaced by an equivalent direct-connected network.

B. Complete Equivalent Network: 6-14

Referred to primary

E_1 = generator voltage (uEg in case of a vacuum tube)

rp = generator resistance

C_1 = distributed capacitance of primary winding, plus any additional. capacitance across that winding.

r_1 = the primary winding resistance

r_c = core-loss resistance

r_2' = secondary winding resistance referred to the primary.

C_2' = the distributed capacitance of the secondary winding, plus additional capacitances across that winding within the transformer itself, referred to the primary.

r_L' = load resistance referred to primary

C_L' = load capacitance referred to primary

E_2' = load voltage referred to primary.

"Additional capacitances" spoken of may be capacitances of windings to ground, or capacitances between windings.

( ) A single-ended interstage transformer might have its primary on the inside, next to the core, and the secondary on the outside wound over the primary.

If the primary finish is connected to +B and the secondary start is connected to ground, there is no a-c potential between adjacent surfaces of the two windings, so that capacitance between the two windings has no effect. However, the primary start layer of the winding has capacitance to the core. This capacitance is an additional capacitance across the primary winding. Similarly, the secondary finish would go to grid and any capacitance existing between the finish layer of the secondary and the core or case would be an additional capacitance across the secondary winding.

If the connections to both windings are reversed, making primary start +B, and secondary finish ground, those capacitances would have no effect. The capacitances between windings, however, would be of great importance. This would be somewhat equivalent to an additional capacitance across the winding having the most turns.

C. Simplified Network at Low Frequencies

At low frequencies, leakage inductance and all capacitances can be ignored.

The low frequency characteristics of any audio transformer are determined by the primary inductance and the various resistances of the networks.

Let $ra = rp + r_1$, $rb = r_2' + r_L'$, then lumped resistance, R, is equal to:

$$R = \frac{rarbrc}{rarb + rarc + rbrc} \qquad (2)$$

If the input voltage E_1 is multiplied by the attenuation of the resistance network, the new value for input voltage is:

$$E = \frac{r_L' rc \, E_1}{rarb + rarc + rbrc} \qquad (3)$$

The voltage output and the phase shift, at low frequencies, of all audio transformers are given by this simple circuit:

At some frequency, $2\pi fL_1 = R$, so that $2\pi fL_1/R = 1$. Let this particular frequency be called f_1. This is the low frequency at which the response has dropped 3db from its value in the middle frequency range. At twice this frequency, $2\pi fL_1/R = 2$; at three times, $2\pi fL_1/R = 3$. At any frequency, f, $2\pi fL_1/R = f/f_1$.

In order to determine the proper value of primary inductance, it is necessary to know what drop in secondary voltage is permissible, at some specified low frequency, as compared with the voltage in the middle frequency range.

As a first approximation (1 db drop) the winding and core-loss resistance may be neglected so;

$$R \doteq \frac{rp\ rL'}{rp + rL'}$$

$$L_1 = \frac{2\pi f L_1}{R} \times \frac{R}{2\pi f}$$

D. Simplified Network at Middle Frequencies

In this frequency range, all reactance elements become negligible, and the transformer reduces to a network of resistances. In this range, phase shift is practically zero. This is the "flat" portion of the frequency-response characteristic, the secondary voltage being:

$$E_2 = \frac{Ns}{Np} \times E_1 \times \frac{rL\ rc}{rarb + rarc + rbrc}$$

and the efficiency of the transformer being to a very close approximation:

$$\text{Efficiency} = \frac{rL'}{r_1 + r_2' + rL' + \left(\frac{rL'}{rc}\right)(2r_1 + 2r_2' + rL')}$$

E. Simplified Network at High Frequencies

The shunting effect of the primary inductance is negligible at high frequencies.

If rp or rL' is less than 20,000 ohms, C_1 may be neglected. Most audio transformers fall in this class.

If rp' or rL is less than 20,000 ohms, C_2 may be neglected. This is usually true of output transformers; it is seldom true of input or interstage transformers.

The core-less resistance, rc, has little effect at high frequencies beyond reducing the secondary voltage by a few percent.

Core loss drop = $\dfrac{100}{1 + \frac{rc}{rb} + \frac{rc}{ra}}$ percent.

Neglecting primary inductance, primary capacitance, and core loss, at high frequencies the term $2(1-k)L_1$ is called the leakage inductance referred to the primary and is usually designated by Le:

$$Le = 2(1-k)L_1$$

OUTPUT TRANSFORMERS

A. Turns Ratio

Turns ratio is determined by the plate load recommended for the tube, or tubes by the manufacture, rL', and the actual load resistance, rL

$$\frac{Np}{Ns} = \sqrt{\frac{rL'}{rL}} \qquad (1)$$

B. Frequency Response

Frequency response is controlled by the amount of primary inductance at low frequencies, and the amount of leakage inductance, at high frequencies.

The voltage output and phase shift of all output transformers at high frequencies are given by the following simple circuit, provided that the load is resistive and that the load and reflected load are less than 20,000 ohms.

(2)

$$E = \frac{rL'\ E_1}{rp + r_1 + r_2 + rL'}$$

$$R = rp + r_1 + r_2' + rL'$$

At some frequency, $2\pi fLe = R$, so that $2\pi fLe/R = 1$. f_2 is the high frequency at which the response has dropped 3db from its value in the middle frequency range. At three times this frequency, f, $2\pi Le/R = f/f_2$.

To determine the allowable amount of leakage inductance, it is necessary to know what drop in secondary voltage is permissible, at some specified high frequency, as compared with the voltage in the

Middle frequency range.

Then:

$$R = rp + r_1 + r_2' + rL'$$

$$Le = \frac{2\pi fLe}{R} \times \frac{R}{2\pi f}$$

C. Efficiency:

Efficiency: Maximum efficiency is obtained for a given physical size and core material, when:

copper loss = core loss

primary copper loss = secondary copper loss

If the secondary resistance, r_2, is made 5% of the load resistance, rL; if the primary resistance, r_1, is made 5% of the reflected load resistance, rL', and if the core-loss resistance, rc, is made 10 times the reflected load, rL', the losses will be very nearly balanced and the efficiency will be 82%.

D. Push pull Output Transformers, Class A.

The generator resistance, rp, is twice the plate resistance of the tube.

The reflected load, rL', is the recommended tube load, plate to plate.

E. Push pull Output Transformers, Class B

One half of the primary works during one half-cycle, the other during the other half cycle. It is important that the two halves of the primary be closely coupled, so that the cross-over from one to the other may be accomplished smoothly and without transients. It is also important that each half of the primary be coupled equally to the secondary. Otherwise, the high frequency response of the transformer will not be the same for both half-cycles, which will produce even harmonics in the output wave. In general leakage inductance should be kept to the minimum between the windings of a class B output transformer, even beyond the requirements of frequency response.

F. The Modulation Transformer

The Modulation transformer is an output transformer, which has as its load the plate of a class c radio frequency amplifier. The audio frequency generator is usually a class B amplifier. (refer to above discussion)

With either type of transformer, the load consists of the grid circuit of a vacuum tube, and its impedance is very high (ie, megohm.). It is often no more than the input capacitance of the tube, although sometimes a resistor of 100K to 500K ohms is placed across the secondary, also. With such a high impedance load, the secondary winding capacitance is not negligible. The secondary winding capacitance and the load capacitance, together largely control the high frequency response and the turns ratio of the transformer.

A. Frequency Characteristics, Low and Middle Frequencies: Refer to Audio-Transformers.

If there is no resistance load on the secondary; that is, if $rL' = \infty$, the equations become simpler:

$$E_2 = \frac{Ns}{Np} \times E_1 \times \frac{rc}{ra + rc}$$

$$\text{Efficiency} = 0 \qquad (1)$$

B. Frequency Characteristics, High Frequencies. (If there is no secondary resistive load.)

It is convenient to express the performance of this circuit by means of a family of curves, plotting voltage ratio vs. frequency. It is seen that the shape of the desired frequency-response characteristic determines the value of a constant, N, while the position of the frequency band determines the value of the resonant frequency, fo.

Then:

$$\sqrt{\frac{Le}{C'}} = N(rp + r_1 + r_2') \qquad (2)$$

And:

$$\sqrt{LeC'} = \frac{1}{2\pi fo}$$

From these equations the value of the leakage inductance, Le, and of the reflected secondary capacitances, C', which will give the desired frequency response can be calculated.

C. The Turns Ratio

The turns ratio of an input or interstage transformer is determined by the secondary capacitance; that is, by the sum of the secondary winding capacitance, C_2, and the input capacitance of the tube, CL. Call this total capacitance C, and let its value reflected to the primary be C'. The correct value of C' is found from the frequency response requirements. Then:

$$\frac{Ns}{Np} = \sqrt{\frac{C'}{C}} \qquad (3)$$

The input capacitance of the tube is given by the formula:

$$CL = Cgf + Cgp(1+u)$$

Cgf = static capacitance between grid and filament

Cgp = static capacitance between grid and plate

u = effective amplification of tube.

Driver Transformers

The driver transformer couples the plate of the driver tube, to the grids of the Class B amplifier.

A. Turns Ratio:

The turns ratio of the transformer must be selected so that the change in load resistance has a negligible effect on drive tube distortion, a condition which is satisfied by using a step-down ratio.

B. Frequency Response

Primary inductance should be high enough to give the desired low frequency response with rL = D. Leakage inductance should be low enough to give the desired response when $rL = \frac{\text{peak grid voltage swing}}{\text{peak grid current swing}}$

C. Leakage reactance

Leakage reactance in the driver transformer is a reactance in series with the grids of the Class B stage.

Leakage between primary and secondary must be kept to a minimum.

It is also important that each half of the secondary be coupled equally to the primary; otherwise, the secondary voltage, at high frequencies, will not be the same for both half-cycles, which will produce even harmonics in the grid-voltage wave.

Capacitances of the windings and input capacitance of the tubes have very little effect upon frequency response or distortion. However, they may resonate with the leakage reactance at some superaudible frequency to cause parasitic oscillations of the B Class stage. Such oscillations cannot be suppressed by means of series grid resistors without increasing distortion. It is desirable, therefore, to shunt a small capacitance from each Class B grid to ground.