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Notes on Measurement and Design of Audio Frequency Transformers

By J. KELLY JOHNSON
Research Engineer, Pacent Electric Company, Inc.

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IT IS not the purpose of this paper to attempt to improve on those various ones covering different phases of the subject in hand which have been presented before bodies of similar character recently. From a more than casual survey of the audio-frequency transformer situation, it seems rather clear that the crying need at the present time is for an orderly and systematic arrangement of the available information. Though this might be done in a mere catalog index form, it is a fact, unfortunate perhaps, but true, that few in the general field have the ability or inclination to tackle the involved technical form in which most of the contributions have been made.

It is the purpose of this paper to present in a simple, practical form the general considerations involved in the design of audio-frequency transfer apparatus, and the results of investigation into the special features of particular applications. A distinct effort has been made to avoid awesome mathematical explanations and to introduce assumptions in a logical order, rather than springing them all at once.

The curves exhibited are first hand, except when specified otherwise, are solely for illustrative purposes, and are intended to show comparative rather than absolute values. They have been taken in the radio laboratory at Columbia University with the coöperation of the Engineering Department of the Pacent Electric Company.

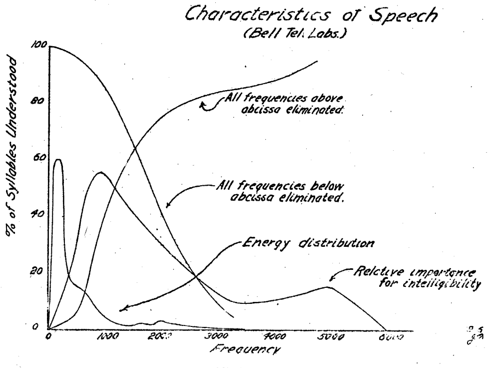


FIG. 1

There are in general two distinct classifications into which audio-frequency transformers will fall. Transformers as used to-day are for voltage or power transfer. A voltage transfer instrument will transmit an alternating voltage with the desired ratio of initial to final magnitudes with a minimum infidelity of wave form, under conditions of very light load. A power transfer instrument will transmit an alternating current at the desired ratio of input to output with a minimum infidelity of wave form, under its rated conditions of loading. There are occasions where one transformer must be designed to function satisfactorily as either a voltage or a power transfer device.

Voltage step-up transformers are normally used between audio-frequency stages. It is important for fidelity of reproduction that the voltage change very little over the range of audible frequencies, and the normal range of applied voltages.

It is generally conceded that frequencies below 30 cycles and above 5000, do not noticeably affect fidelity by their absence. The curves in Fig. 1 are from the Bell Laboratories and illustrate this point. The curves showing per cent. of intelligibility indicate that within the above limits, speech is about 98 per cent. understood. This is ample for nearly all purposes. Although the most important frequencies are near 1000 cycles, still up to 5 or 6000 cycles the curve is fairly high. The frequencies below 300 cycles contain nearly all the energy of the voice, or of music. It is, therefore, necessary to transmit these in order that the effect of bottom or fullness of tone may not be lost. The deepest organ tones are seldom below 30 cycles and the highest violin note is below 5000 cycles.

The amplifier as a whole acts as a band-pass filter of which the coupling transformer is an element.

MEASUREMENT OF OUTPUT VOLTAGES

THE measurement of output voltage of voltage transformers must be done without excessive loading. This elimi-

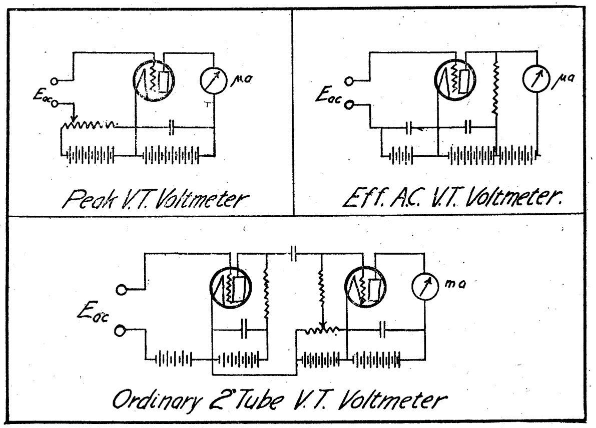


FIG. 2

nates ordinary a.c. instruments. The electrostatic voltmeter might be used, but the voltages to be measured are normally too small and the internal capacity of the meter too large.

The vacuum-tube voltmeter in some of its many circuit variations is very satisfactory. The maximum input voltage (a.c.) to the primary of an audio-frequency voltage transformer varies from nearly zero to maxima of 80 on the primary of the transformer feeding two 250's in push-pull, and 0.4 on the primary of the transformer feeding the first tube of a 201-A, 171-A combination.

It is clear that a single voltmeter cannot be used satisfactorily over the whole range. Fig. 2 shows some standard variations of voltmeter circuits.

The first and simplest is a peak voltmeter, where the plate current is set at zero and the grid bias adjusted to give again a zero plate current after the application of the a.c. on the grid circuit. This gives the peak value, cannot normally be used on distorted waves, and is capable of about 2 per cent. accuracy when in the hands of an experienced operator. It requires an expensive meter in the plate circuit; a microammeter or good galvanometer being usually employed.

In the compensated type, the tube is biased to the point of maximum curvature of the I_p—E_g, curve and a sensitive d.c. meter in the plate circuit has the normal plate current bucked out of it by some such scheme as shown. It is difficult to calibrate this to better than 5 per cent. It is as expensive as the first type, easier to operate but is apt to be more inaccurate.

If sufficient amplifier tubes are added before the detector, very small voltages can be measured, or more insensitive meters may be used. The accuracy, except where very special pains are taken, remains about the same, 5 per cent.

The circuit of the Western Electric D-79017 voltmeter shown in Fig. 3 is an example of refined construction permitting a high accuracy of measurement. It has a frequency range from 100 to 5000 cycles with plus or minus 2 per cent. accuracy between 200 and 3000 cycles. The voltage range is from 3.16 to 0.001 volts and it will measure from 31.6 to 0.02 milliamperes. It is a marvelously flexible and useful precision instrument.

An ordinary one or two-stage amplifier when calibrated over the frequency and voltage range and used with a resistive load and a thermocouple in the output makes a very good vacuum-tube voltmeter. It is best to use an output transformer.

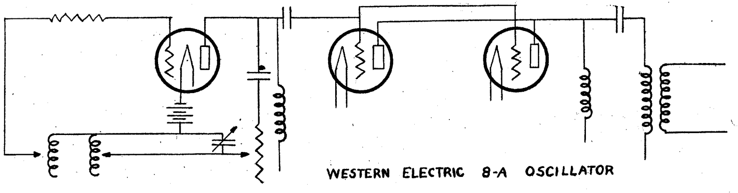
Regardless of the accuracy of the measuring voltmeter or its sensitivity, true curves cannot be obtained unless actual operating conditions obtain, or are simulated.

With normal grid bias on an amplifier tube the loading of the transformer by grid conductance is far greater than it would be with a one tube V. T. voltmeter load. The grid conductance changes sufficiently with a.c. voltage applied to make it quite desirable to specify actual loading conditions, when making the test. The one-tube voltmeter circuit falls down from the very start.

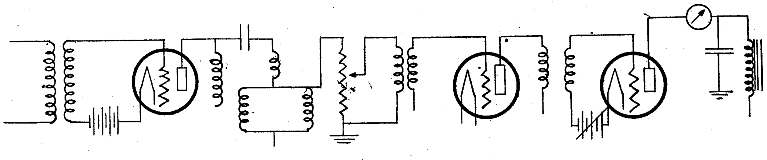
In a two-or-more-tube voltmeter, the first tube may reproduce the loading conditions of the transformer under actual use. If the output circuit of the first tube is kept fairly approximately to actual practice the problem of measuring secondary voltage is practically solved, except for the question of constancy of calibration.

From the input side there are two major considerations. The effective a.c. resistance of the feeding tube must be supplied in order to get the lower frequency characteristic successfully. Also, for some types of transformer especially, the d.c. flowing in the primary must be the same as under actual conditions.

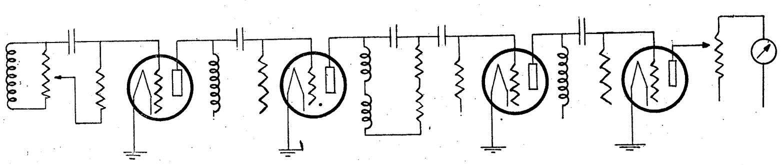
The diagram in Fig. 4 shows a circuit which has been



WESTERN ELECTRIC 8-A OSCILLATOR

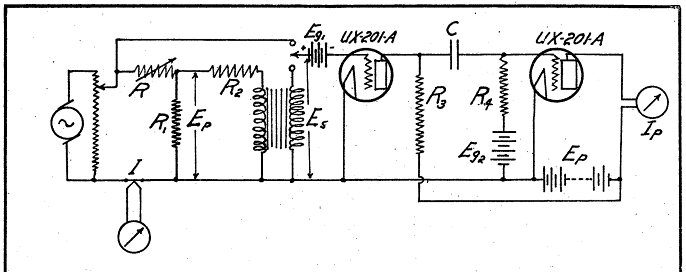


WESTERN ELECTRIC 3 TUBE VOLTMETER



WESTERN ELECTRIC TYPE D-79017 V.T VOLTMETER

FIG. 3



Transformer Ratios
Testing Set-up.

Explanation.

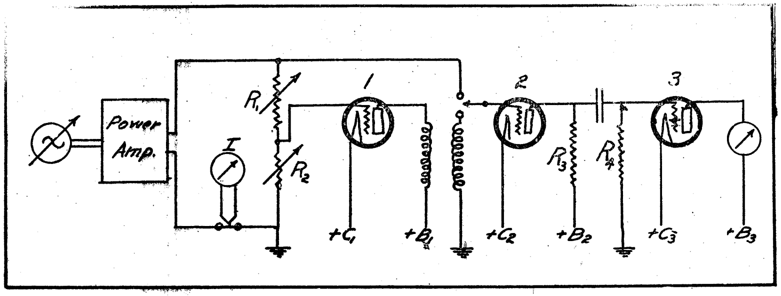
$R = 0\text{-}1000\,\omega$
$R_1 = 25\,\omega$
$R_2 = 12000\,\omega$
$R_3 = 10000\,\omega$
$R_4 = 2\,\text{meg}\,\omega$
$C = .01\,\mu f$
$E_p = .25\,v.$
$E_{g_1} = 4.5\,v.$
$E_p = 90\,v.$
$I = .01\,a.$

FIG. 4

used with most satisfactory results by the writer. To avoid any error in calibration of the voltmeter, a comparison method is used. This permits of a very high degree of accuracy without extreme care in setting the input voltage. An accuracy of 1.0 per cent. is easily obtainable. In addition the circuit is self-calibrating and any change in detector circuit constants is immaterial. They can be adjusted at any time to give maximum sensitivity and ease of reading without introducing error.

In the input circuit, the applied voltage, d.c., and equivalent tube resistance may be adjusted to simulate any type of tube. The current I, through R, is set to give the desired voltage on the primary of the transformer. With the switch down the reading at I_p is noted. Then the switch is flipped up and R adjusted until the same reading is obtained. By rapid flipping of the switch and a low inertia meter a very accurate setting may be made.

This circuit in a modified form is shown in Fig. 5 where a tube is used as input. This is of advantage when the test has been standardized for commercial rather than laboratory use. In this way, actual operating conditions are effectively reproduced.



A.F. Transformer Test Circuit.

Standard Test Constants—

R_1 1000ω-
R_2 100ω-
R_3 .25Ω-10,000ω
R_4 2.0Ω
1 & 2 UX 201-A
C_1 4.5 v., B_1 90
C_2 7.5 B_2 90-135
IR_2 .25 v.

FIG. 5

Figs. 6, 7, 8, and 9 show the effect of variation in applied a.c., d.c., load, both resistive and capacitive, and grid bias of the loading tube on the characteristic curve. They supply ample evidence to justify the specification of measurement under actual load conditions.

Fig. 6 was taken with a single-tube voltmeter using the method of comparisons which greatly increases the obtainable accuracy. The high bias used rendered the effect of grid conductance negligible. The improvement in the transformer characteristic with increase of applied voltage is quite pronounced. To make characteristic curves on transformers comparable, therefore, the same a.c. voltage must have been applied to their primaries.

In Fig. 7 is shown the effect produced by d.c. passing through the primary coil. The dotted curves show that a transformer with a heavy silicon steel core was not much affected, while the curve for the high permeability alloy core transformer was badly damaged by the d.c. The value of current used was about normal for a d.c. type tube and considerably less than those encountered with the new a.c. types. The transformers were recommended by their respective manufacturers for use in the same point in the circuit.

Fig. 8 shows the effect of a resistive load placed on the secondary of a transformer. The peak voltage at resonance is cut down appreciably by even a load of very low conductance. The next, Fig. 9, shows the effect of grid conductance in flattening out the transformer curve. Although the grid did not swing positive, the conductance caused sufficient regulation to flatten the curves as shown. It must be noted that the previously mentioned effect of increased voltage applied on the primary raised the low frequency portions of the 0.5- and 1.0-volt curves and lowered their peaks.

SPECIAL TEST APPARATUS

MEASUREMENTS on power audio-frequency transformers may be made using the same apparatus as described above. Ordinarily, however, the actual loading conditions require the employment of higher voltages than are conveniently measured with this layout.

The fact that these are power transfer instruments immediately suggests the use of standard alternating current voltmeters, ammeters and wattmeters. But, the power required to operate the average a.c. ammeter is often as high as 5.0 watts, and the voltmeters are but slightly more sen-

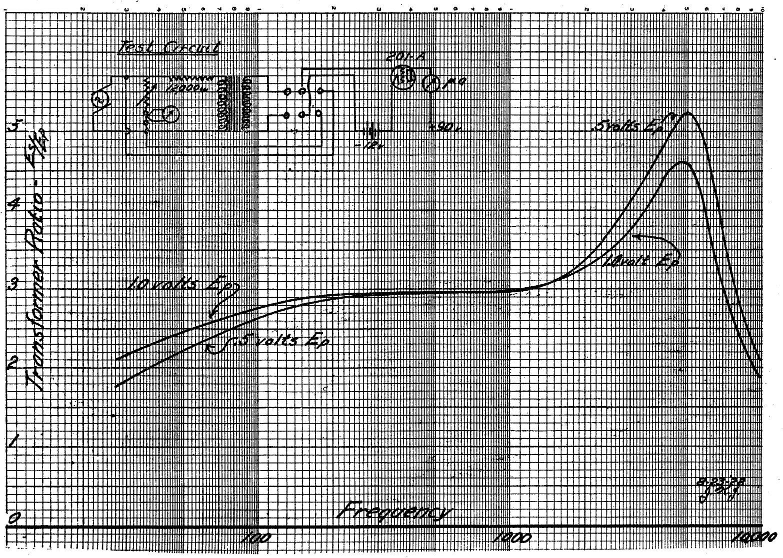


FIG. 6

sitive. Wattmeters, partaking of the characteristics of both voltmeters and ammeters, consume about twice this power. Thus it is seen that ordinarily the total output of the transformer under normal loading is insufficient to operate the meter alone. In addition, the inductance of the iron vane, or dynamometer type of meter movement is quite appreciable, and would give very great variation in indicated voltage values with frequency. The ordinary meter is not accurate beyond one-hundred-twenty cycles.

With again the exception of the electrostatic voltmeter, a delicate, expensive and usually temperamental instrument, ordinary a.c. measuring instruments are not easily adapted to the measurement of output, or power audio-frequency transformer characteristics.

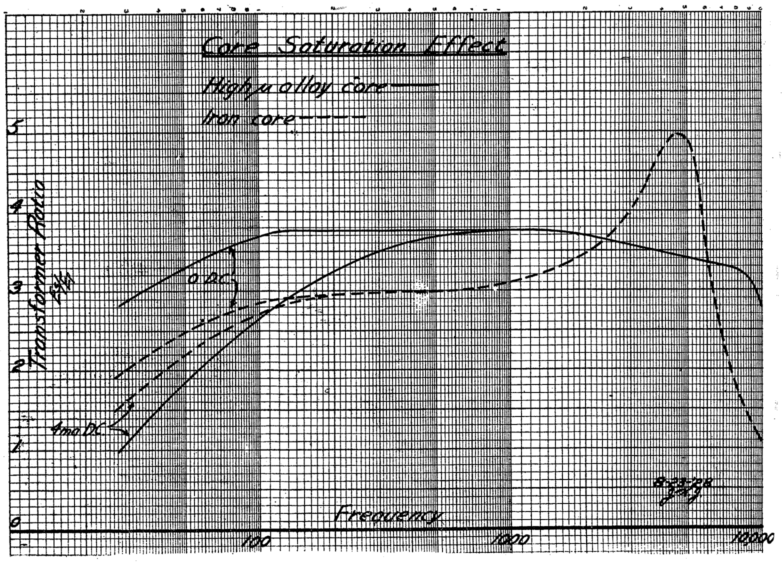


FIG. 7

The circuit used in Fig. 10 is probably the simplest and the first to suggest itself. It requires a thermocouple meter and resistor to fix the input voltage, and another to measure the output voltage. This makes necessary a "mark" reading or requires an oscillator of a high degree of stability and high power output.

The V.T. voltmeter comparison method can be used to advantage, a single tube voltmeter with a direct indicator in the plate being sufficient, as the output voltage of the transformer is high, and the added loading of the measuring device low enough to be neglected. It is possible that an inverted V.T. voltmeter might be evolved which would simplify measurements.

As regards the simulation of loads for power transformers, the curves of Fig. 10 show how a characteristic is altered by the secondary load. At the low frequencies the load reflected from the speaker would give a very low impedance load on the tube, while at high frequencies the opposite is true. A resistive load, on the other hand will not have unpredictable resonance points as shown on the speaker curve and will give a fairly constant reflected load. In view of the fact that many types of speakers might be used any of which might well vary with time or change of manufacturing conditions, it is probably best to use a resistive loading, preferably one of twice the a.c. tube resistance, for a one to one transformer. This will make it possible to compare various transformers against a standard with the greatest ease.

To supply the power required for operating these transformers at their rated loads, an oscillator with large power output and a stable frequency characteristic is needed. This means a stable oscillating tube circuit, and a power amplifier.

The Western Electric 8-A oscillator circuit is probably as stable as necessary, is capable of holding its calibration well, and is reasonably simple in construction and operation. It is used by several commercial manufacturers of laboratory apparatus. It has, as shown in Fig. 3, a shunt-feed, tuned plate circuit, with tapped or interchangeable inductances. It is usually best to adjust the feedback so as to just barely produce oscillations. This improves the curve form by minimizing the production of harmonics.

The output of the oscillator is fed to an amplifier which constitutes only a very light load on the oscillating circuit. This amplifier should be of the push-pull type in order to reduce tube distortion effects. This also increases the power output available. Push-pull 171's will give 3.0 to 4.0 watts output at 100 volts if a 1:1 output transformer is used. This means 40 mils a.c., which is normally sufficient. If a greater current is needed, the output transformer ratio can be reduced, increasing the current, but lowering the available voltage.

The art of transformer design is by no means new. Before the Edison system was developed in America, Europe was using alternating current machinery and coupling power-using devices by means of transformers. The design of iron core transformers is probably as completely mastered as any one design field concerned with electrical machinery. It is, then, a very surprising thing that there have been so few of the well-known principles of transformer design applied to audio-frequency coupling transformers. It might be of considerable advantage to review a few of the salient features of power transformer design, as it is to-day.

TRANSFORMER TYPES

THERE are two distinct types of transformer in commercial use. These are the shell and the core types. In Fig. 11 the distinguishing features of both are noted. The core type, with a half primary and a half secondary on each leg, is often used in a high tension installation. The length of the coil adapts itself to the winding of many turns of fine wire. The shell type is well adapted for use in heavy current work, as the sectional arrangement of the windings permits the use of heavy ribbon wire which is easily wound. As far as satisfactory performance is concerned one type is about as good as another.

There is no iron wastage in cutting the laminations for the core type transformer, since the four legs are each made of rectangular sheets lapped at the corners. This construction is not so rigid as the shell type, which uses E-I, F or more complicated interlocking sheets. In the very large sizes, of course, the shell type core is also built up of rectangular sheets. Small power transformers are nearly always of the core type though there is a tendency in the radio field to design shell type cores for alternating current set power transformers. The cheapest commercial jobs are usually core type.

In the shell type insulation between layers may be very little, greatest attention being paid to insulating one section from another, as the greatest voltage is developed here. In the core type the insulation between layers is very important, as high voltages are developed due to the length of the layers.

Transformer efficiency is the highest of any unit in an electrical system in modern commercial practise. It reaches as high as 98½ per cent. in some large units. Assuming that the transformer is to be worked at full load, the copper loss should be made equal to the iron loss and should be equally divided between primary and secondary. This means that the primary equivalent resistance is a trifle lower than that of the secondary due to the allowance made for magnetizing current. Transformer losses may be readily and accurately calculated by standard handbook methods.

The following table of design constants will give an idea of present day practice:

TABLE I

$\frac{\text{Core Width}}{\text{Core Length}}$	2.6
$\frac{\text{Window Width}}{\text{Window Height}}$	1.5
Per cent. no load current	1.3 to 12
Per cent. Core loss	.8 to 2
Per cent. IX drop	1.3 to 4
Flux Density	35 to 67 KL per in.²
Efficiency	96 to 98%

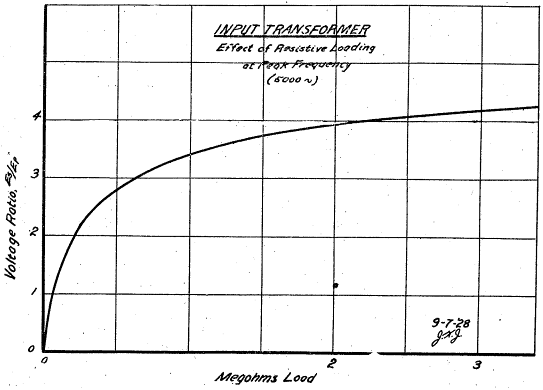


FIG. 8

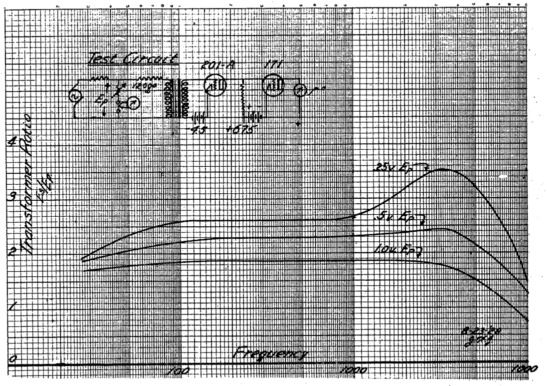


FIG. 9

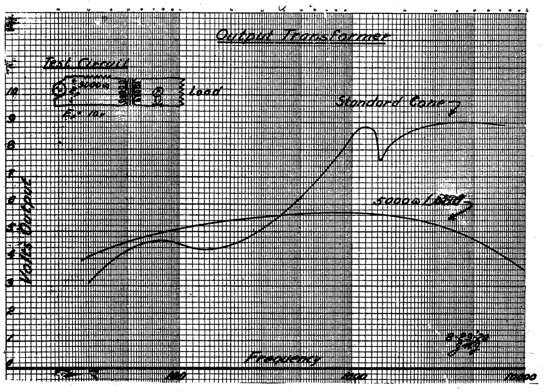


FIG. 10

A voltage regulation of 5.0 per cent. under full load is considered excessive. The coefficient of coupling is usually between 99.5 per cent. and 100 per cent.

First consider the design of an output transformer for a vacuum-tube audio-frequency amplifier. It must transmit the audible range of frequencies with the greatest possible fidelity both as to wave shape and amplitude. It is moreover a power transformer and must deliver power to its load with very slight loss. Before attempting a design a few criteria must be established.

TYPES OF DISTORTION

THERE are two major types of distortion occurring in an audio-frequency amplifier. The first is wave shape distortion, or the introduction of harmonic frequencies not in the original wave. The second is amplitude distortion. There are several causes for each of these.

Wave shape distortion may be caused either in the tube or the transformer. A curved tube characteristic or d.c. saturation in the transformer will produce even harmonics of the initial wave, and a.c. saturation in the transformer core will produce odd harmonics. Tubes are usually worked on as straight a portion of their curve as possible, or are connected in push-pull so as to eliminate the effect of the even harmonics. The only remedy for distortion introduced by transformer saturation is to run the transformer core at low flux densities where the magnetization curve is practically straight. Fig. 12 shows the magnetization curve of a standard type of transformer. It is very straight indicating that there is little a.c. saturation effect. If the core were magnetically biased with direct current, saturation would begin to be visible. If the frequency of the applied voltage were reduced, the current would be increased and saturation would occur more quickly. It is important to note that at very small applied a.c. voltages the inductance of the transformer is lower than at high applied voltages, which gave the effect shown in Fig. 6, where the curve rose with applied voltage at low frequencies due to this increase of effective inductance.

Amplitude distortion may be divided into two classes. In the first, the output voltage of the amplifier is not directly proportional to the input voltage. As noted above, at low frequencies low voltage inputs will not be amplified as much as higher ones due to the change of inductance of the transformer primary. The second class is that of frequency discrimination. Certain characteristics of the transformer and associated circuit cause it to pass some frequencies with less loss than others.

In Fig. 13 are shown the actual circuit diagram, the equivalent diagram, and the vector diagram of the loaded transformer. The effective alternating current plate impedance of the tube must be added to the effective primary resistance of the transformer. As shown in the vector diagram, the leakage reactance causes a voltage drop in quadrature with the effective resistance in both the primary and secondary which causes voltage regulation. The greater the load, the greater the regulation from these causes. It is therefore desirable to have the effective tube, primary and secondary resistances as low as possible in order that the voltage output may be proportional to the voltage input.

Fig. 10 shows a curve of output voltage against frequency for a resistive load. With a constant voltage input the curve drops off at both ends. The drop at the high frequency end is due to the leakage reactance whose effect increases with frequency. The drop at the low end is due to the increasing magnetizing current causing magnetic saturation of the core, and increased IR drop in the primary circuit. The leakage reactance can be neglected where this effect comes in.

The cone speaker load curve introduced on the same sheet shows the effect of an impedance load which is low at low frequencies and high at the high ones. A resistive load is better for test purposes, though it is known that an inductive load is to be applied. An inductive load in general increases the regulation of a transformer.

It is clear that the effective resistance and leakage reactance of the output transformer must be reduced as much as possible. A generous sized core and heavy winding will take care of the former while reference to the drawing of core and shell type transformers (Fig. 11) will show how to reduce the latter. In the core type the closer the coils to each other and the iron the lower the leakage reactance. The same is true in the shell type with the additional note that the more the sections of primary and secondary are interspersed, the lower the leakage.

In designing an output transformer, some design frequency should be chosen as a basis of attack. It is probably as well to use 100 cycles as any, although some might prefer to use 120 cycles as more conventional. First the transformer magnetizing current may be assigned as a certain per cent. of full load current. Of course, full load current and voltage must be known before ever attempting a design. A 10 per cent. no load current at full load voltage is quite permissible at this frequency. Assume a square inch of core and a reasonable average length of magnetic path. Calculate the ampere turns required to produce a flux density of about 40 KL per square inch. Calculate the inductance that this number of turns would give. These calculations may be made by standard handbook formulae. Keeping the flux density in the core the same, choose that size of core and number of turns which will give the required inductance. The inductance required is—

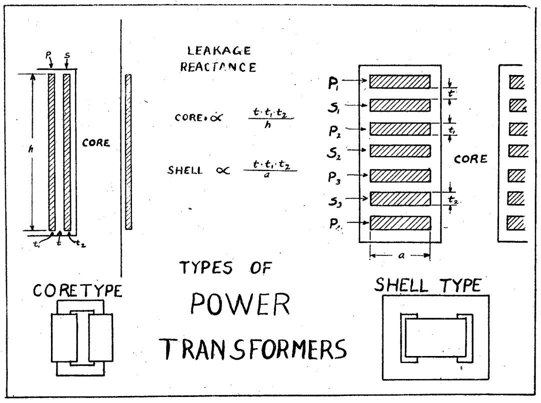


FIG. 11

$$L = E/2\pi f I_{00}$$

where F is the base frequency
I_{00} is the permissible magnetizing current.
E is the maximum primary voltage.

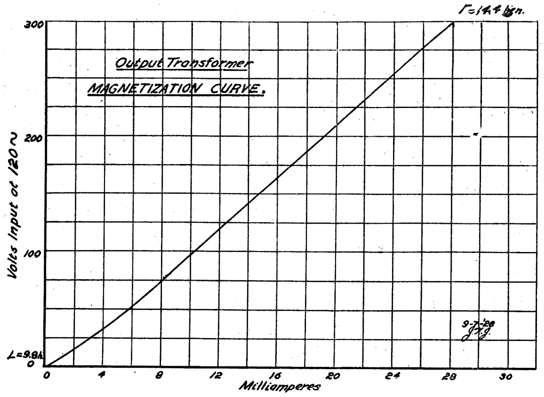


FIG. 12

It may be considered more economical to design the transformer for the normal applied voltage instead of the maximum, in which case the inductance will not have to be as high. A correction for the d.c. in the core may be made, if desired, but it is usually sufficient to choose a flux density rather low to make allowance for this.

The rest of the design consists in fitting in the required coils. Allowing a 2.0 or 3.0 per cent. drop in resistance at full load, the primary and secondary resistances may be calculated for any desired ratio. A rough estimation of the probable length of turn is sufficient in this calculation. Data are available from coil manufacturers giving turns per square inch and formulae for calculating available winding space. From these the window size may be calculated. It will probably be necessary to go over the design several times in order to compensate slightly incorrect assumptions. The efficiency and regulation may be calculated from standard handbook formulae.

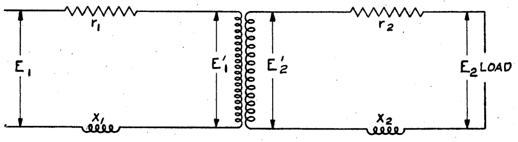
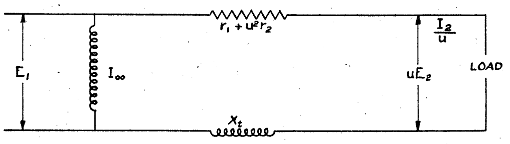
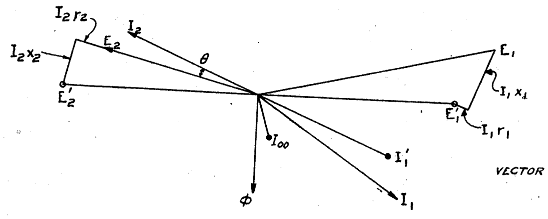


DIAGRAM OF CIRCUITS



EQUIVALENT CIRCUIT



VECTOR DIAGRAM

FIG. 13

In proportioning the window it is important to remember that for low leakage reactance it is necessary to keep the wire as close as possible to the iron and to split and intersperse primary and secondary in the shell type.

Interstage transformers are usually voltage amplifiers. That means that they are practically unloaded. The primary impedance still plays the major part at the low frequencies and can be calculated to secure a chosen per cent. of the total plate circuit voltage drop.

It is again very important to keep the flux density in the core below the knee of the saturation curve on the straight line portion of the magnetization curve in order to reduce odd harmonics. In this connection it is well to recall the saturation effects in high permeability metals as compared with electrical steel. Special high permeability alloys become saturated at very low flux densities. Even though the primary inductance may remain high enough to secure practically all of the voltage in the plate circuit, the variation in inductance due to variation in permeability of the core during the cycle of the alternating current wave, will introduce strong odd harmonics. It is necessary to be very careful in specifying special alloy cores for audio-frequency transformers.

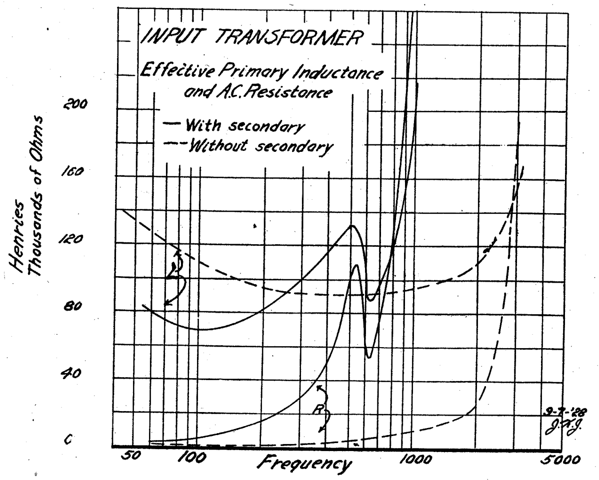


FIG. 14

Fig. 14 illustrates the effect on the apparent resistance and inductance of the primary circuit of a voltage transformer, of the addition of a secondary circuit. The added losses are very noticeable, the added capacity lowers the resonant frequency and the loading lowers the effective low-frequency inductance. A coupled circuit effect produces an added jag in the curve about midway, and there is some parallel resonance effect at low frequencies. This curve illustrates the way a voltage transformer load looks to the tube which is feeding it.

Therefore, the actual and equivalent circuits of the voltage transformer must include the distributed capacity of the secondary to enable a correct design to be worked out. In the equivalent circuit the leakage reactance is in series with the effective resistance and the distributed capacity of the secondary and the associated circuit. Of this asso-

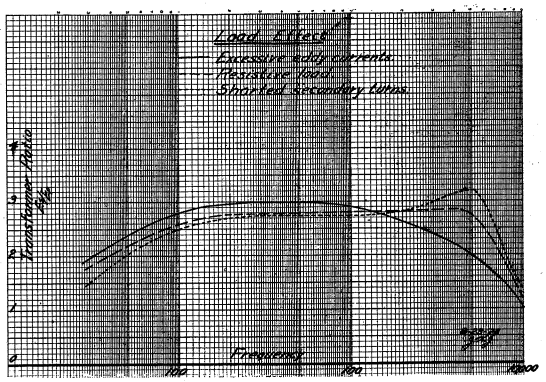


FIG. 15

ciated capacity a large portion is formed by the effective tube capacity which is—

$$c^{1}_{gf} = c_{gf}\,(u+1)\,c_{gp}$$

At some frequency the circuit will be in series resonance and will give a high voltage drop across the capacity due to the resonant current. This produces a peak on the characteristic curve of frequency vs. ratio, as was to be noted in several of the Figures. If the effective reactance and capacity can be made small enough the peak may be moved out of the normal range of transmitted modulation frequency. If the effective resistance is increased sufficiently the resonant current can be reduced to a value which will not produce a prominent peak.

Fig. 15 shows the effects of obtaining this resistance increase in various ways. For straight resistive loading, a load is placed across the secondary, and sometime the primary, or the copper resistance is increased. This last method is not very effective and has some very bad faults. Short-circuiting turns are frequently supplied by soldering a thin metallic band about the primary. Increased eddy current losses are obtained by using heavy laminations, low lamination resistance, and low resistance steel. It is seen that both resistive shunting of the secondary and short-circuited turns will lower the gain ratio. There are a number of manufacturers, however, who use these methods. Loading by eddy currents, on the other hand, does not appreciably reduce the gain at low frequencies, but does flatten the peak at the high frequencies since eddy currents are proportional to the square of the frequency. It also cheapens the construction of the core. It is rather more difficult to control than the other methods of loading.

In Fig. 16 are shown curves for various improved designs of audio-frequency voltage step-up transformers. By pie winding, sufficiently low distributed capacity and leakage reactance are obtained to put the resonance frequency peak above the normal range of the radio-frequency band-pass of a receiving set.

The curve shown for the transformer with a small window is an example of the tendency toward improvement in transformer design. This had a comparatively small core weight and a high primary inductance, but showed practically no tendency to saturate with normal d.c. applied.

The small type transformer whose curve is shown, is interesting chiefly because of the method of manufacture. It is wound with a high space factor so that the turns in a layer bunch up during winding. This automatically short-circuits enough turns to iron out the resonance peak. The cheapness of the core, winding and assembly enables this transformer to compete successfully with a much higher grade product.

By careful consideration of the above points, it is possible to design transformers to give almost any type of amplification curve that is desired. It may be made sloping up to high or to low frequencies, or as flat as desired. Transformers for television may be made which will pass up to 30,000 cycles and down to 300. There is an authentic and interesting case where a transformer was designed to, and did, pass from 0.1 cycle per second to 2000 cycles per second with a flat characteristic. The primary had an inductance of 18,000 henrys, and the secondary 80,000.

A carefully designed voltage transformer with a value of primary inductance to give a 3.0 per cent. drop at sixty cycles with a 10,000-ohm tube, that is, 110 henrys, can be made with such a low leakage reactance that it will peak at above 7000 cycles. If the core laminations are so made that the eddy currents are large, they will increase the effective resistance sufficiently to flatten the resonance peak completely. This will not affect the gain over the lower frequencies, however. Such a transformer is fully sufficient for covering the range of frequencies which were cited in the first of this paper as constituting a perfectly satisfactory reproduction of voice or music.

The design of current or power output transformers, it is repeated, must follow very closely the principles of commercial power transformer design. These are even more applicable to this type than to the voltage transformer. In output transformers capacity is not of such vital importance, and effective resistance and inductance come to the fore. A satisfactory output transformer may be designed practically entirely by large power transformer design procedure.

In conclusion, the writer wishes to express his appreciation of the assistance in compiling this data rendered by the Engineering Department of the Pacent Electric Company.

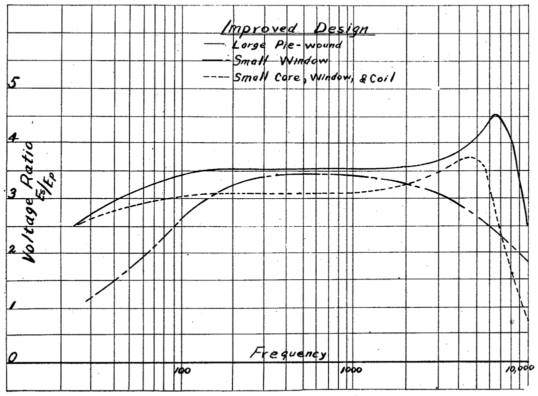
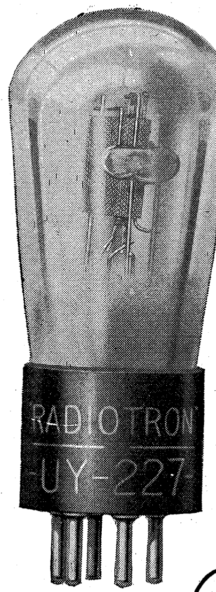


FIG. 16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Their very manner of existence and daily accomplishments tell all that the onlooker needs for appreciation and endorsement.

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Glowing praise is irrelevant when this exists. It is enough to hear on all sides the quiet remark, "Kolster is a fine set."

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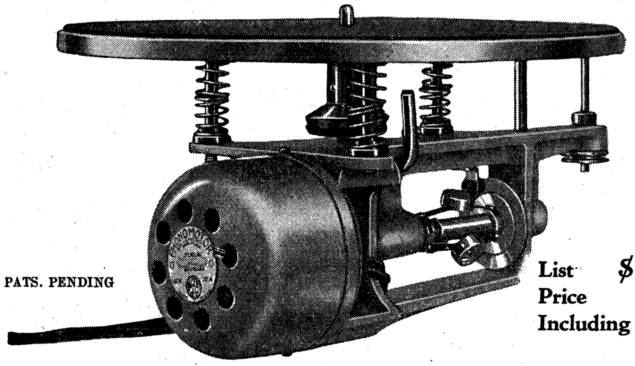
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