

Output Transformers and magnetic formulas

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Revised 2004-09-16

1 Disclaimer

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2 Introduction

Output transformers for tube amplifiers have long been seen as some kind of “mystery” component and many rumours and misconceptions circulate regarding what is to be seen as good or bad transformers. It is also sometimes taken for granted that making good transformers is so difficult that it is best left to experts, I don’t think anyone should take this view for granted.

I will in this paper present methods of designing transformers that can be applied by any DIYer and will give very good results even though it maybe can’t be compared to the best professionally made transformers.

I wrote this paper partly as a response on some contributions I have seen on DIYaudio.com and other DIY forums where it sometimes is argued that transformers from a certain manufacturer are superior and usually one or 2 parameters are mentioned as proof. It could be so that the transformer presented is as good as the author say it is but as will hopefully be understood by this text all transformers are compromises and many parameters need to be compared before a full understanding of the full performance is achieved.

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3 Compromises

Transformers in most simple form consist of a primary winding and a secondary winding that are wound round a metallic core. The windings are usually wound on an isolated former called a bobbin.

The design of an audio transformer is a process full of compromises; here are some guidelines and considerations:

Physical core size is determined on the power and low frequency limit that is needed, however the larger the core the more winding capacitance there will be limiting bandwidth. High frequency bandwidth is also dependent on how the windings are sectionalised, the more sections the lower the leakage inductance will be but this is also a compromise with winding capacitance that will increase when many sections are used.

Choice of core material also affects the performance of the transformer. High permeability materials make it possible to design high bandwidth transformers but such a transformer is also very sensitive to DC magnetisation.

4 Core types

All cores used for tube output transformers are laminated that, is they consist of many thin layers of metal plates put together, lamination enables reduction of core losses as it reduces Eddy currents.

4.1 EI cores

EI cores are the most common, they consist of one part that is in shape of an E and another part that is in shape of an I. Advantages of EI cores are that they are cheap and easy to produce and they are easy for the DIYer to dismantle and put together again. The major disadvantage is that EI cores can not benefit in the same way as C-cores and Toroidal cores when using grain oriented transformer material as some field lines will always be perpendicular to the grain orientation which reduces max allowable flux level.

4.2 C-cores

C-cores are wound in tape form on a rectangular mandrel, impregnated and cut into halves that take the shape of C's. The ends of the 2 halves are polished so that they can be put back together without any air-gap.

After the bobbins have been winded they are put on the C legs and the 2 C Halves are put together, depending on design the 2 C halves are kept together using glue, an outer case, an outer steel band that goes around the whole core or in some cases the 2 halves are welded together. A major advantage is that C-cores can be made using grain-oriented metal which allow for higher flux and higher permeability which gives lower loss and smaller core area for a given power level. C-cores are also suitable for the DIYer if they can be dismantled which normally is possible except in the case when the core is welded.

4.3 Toroidal cores

C-cores are wound in tape form on a circular mandrel and then impregnated. A difference between the Toroidal core and others are the way of winding, for Toroidal cores a bobbin is not used; instead the winding is done directly on the core using a special machine. The major advantage with Toroidal cores are that they can be using grain-oriented metal which allow for higher flux and higher permeability which gives lower loss and smaller core area for a given power level, even higher than for C-cores as there is less core losses. Disadvantages with Toroidal cores are that they are not really suitable for DIY as a special winding machine is necessary and also that they are more sensitive for DC imbalance.

5 Core materials

5.1 Silicon steel, non- and grain-oriented

The most common transformer core material is silicon steel which is steel alloyed with ~3-5% Silicon. Silicon steel can be manufactured non-oriented or grain oriented, in grain oriented steel all grains are oriented in more or less the same direction which make the magnetic losses in the material less than in non oriented material.

5.2 Cobalt iron

This is an alloy containing Cobalt 35 – 50%, expensive and unusual for tube output transformers. Advantages are very high saturation limit with a Bmax of ~24000 which make it possible to make smaller transformers for high power.

5.3 Nickel iron

Alloy with high nickel content ~35 - 70%. Advantages, different properties depending on exact alloy but most common alloys for audio transformers have higher permeability than silicon iron making it possible to make transformers with less turns and therefore better bandwidth.

5.4 Other alloys

There exist many other alloys for use in transformers like “Permalloy”, “Mumetal” among others; these are sometimes used for shielding or for low power input or inter-stage transformers.

5.5 Summary of materials

Material	Permeability		DC saturation limit, Gauss	Typical max AC operating flux, Gauss
	Initial, μ_i	Max, μ_e		
Silicon steel non-oriented	400	7000	20000	14000

Silicon steel grain-oriented	1500	35000	20000	16000
Cobalt steel	650	10000	24000	20000
Nickel steel	9000	50000	16000	13000
Super-permalloy	55000	500000	7000	5000

Values are for typical materials; there are quite big variations between different manufacturers especially for the non-silicon alloys.

Note that DC saturation limit and AC operation flux limit is lower for high permeability materials which actually means that the core need to be larger for a given power level. Also important to realise is that high permeability materials are more susceptible to core saturation when DC current is applied.

5.6 Choice of core type and core material

To choose the best core type and core material is not very easy but I believe that C-cores using grain-oriented silicon steel are probably the best compromise. This core have high saturation limit, is relatively inexpensive, is not so sensitive to DC magnetisation and can be used with air-gap if needed, it is also a core type that is suitable for the DIYer.

Nickel alloys have high reputation and some manufacturers want you to believe that these are much better than ordinary silicon steel cores but important to note is that these cores need to be larger than silicon steel cores for the same power level and this material is also are more sensitive to DC magnetisation. They are however good for input and inter-stage transformers.

Toroidal type cores also look very good on paper but have 2 main problems; they are the most sensitive to DC magnetisation and are also more difficult to wind in sections making it very important to chose a good manufacturer. They are also not suitable for the DIYer as they are difficult to wind without special machines.

Regarding sensitivity to DC magnetisation it should be noted that DC balance between tubes in a push-pull amplifier can change when the tube ages. Ideally a push-pull stage should be rebalanced now and then.

Another cause of unbalance in the transformer is dynamic unbalance between the tubes, this will show itself as even order distortion even though the tubes are DC balanced and if dynamic unbalance is large the transformer can saturate on signal peaks which will limit low frequency output power.

I therefore don't recommend Toroidal type output transformers unless the tubes are carefully matched both static and dynamic and also that there is a DC balance control included in the circuit.

5.7 Interleaving

In order to reduce leakage inductance and inter-winding capacitance interleaving of the windings is used, that is the windings of the primary and secondary are divided into several sections when they are wound on the bobbin. Generally the more sections that are used the coupling improves thereby reducing the leakage inductance. However inter-winding capacitance increase with increased interleaving which make it important to reach a suitable compromise in order to achieve the correct balance between leakage inductance and inter-winding capacitance.

Many output transformers are wound using 5 primary sections and 4 secondary sections; this seems to be the best compromise in many cases. For push-pull transformers it is also common to use 2 parallel sections, (horizontal interleaving) which make it possible to achieve that the sections are exactly equal and have the same winding resistance, the Williamson transformer that is described in section 11 is wound using this method.

6 Reading transformer data sheets

Maybe it is not surprising that companies producing tube amplifier output transformers as every other manufacturer is trying to show their products as favorable as possible. Especially when it comes to output transformers there seem to be no standard way for the conditions at where parameters are measured which means that almost every manufacturer seem to give their product data measured under different conditions.

6.1 General

In general it is important to compare 2 transformers during the same conditions, i.e. primary source impedance, secondary load impedance and power level must be the same for the transformers compared otherwise the comparison is more or less meaningless, it is possible to recalculate values for one set of conditions to others but it is usually difficult as normally not all parameters are given in the datasheet.

Normally it is easier to design a transformer for lower primary impedance and for lower turns ratio so such transformers usually show better performance on paper.

6.2 Primary inductance

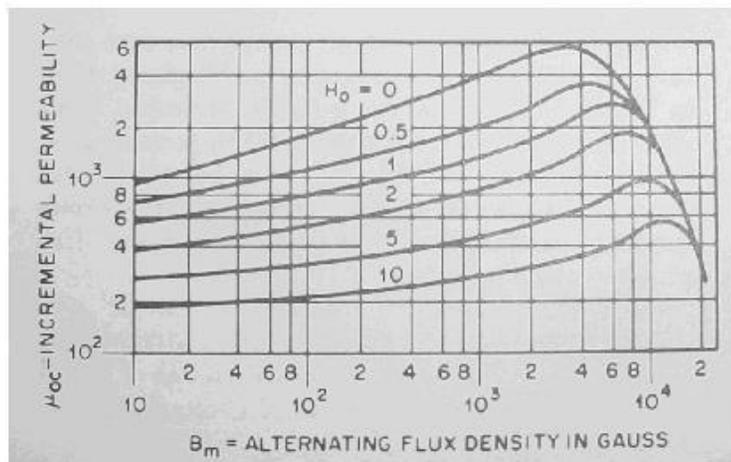
Primary inductance is dependant on the degree of magnetisation; the inductance is highest for a certain magnetisation and is lower for low and very high magnetisation.

The magnetisation and therefore the inductance is dependant on the applied AC voltage according to the formula described above:

$L_p = 1.257 \times \mu_e \cdot N^2 A_c \times 10^{-9} / L_c$, where μ_e is dependant on the magnetic flux density B which can be calculated from:

$$B_{AC} = V_{r.m.s} \times 10^{10} / 4.44 \cdot N \cdot f \cdot A$$

As an example for standard 4% Silicon steel the μ_e reach a max of ~6000 for a B of ~4000 Gauss but is only 1000 for low B of 10.



Incremental permeability μ_{ac} characteristics for audio transformer iron lamination with 4% Silicon, H_0 is DC magnetising field in Oersteds

6.2.1 Primary inductance in SE transformers

Transformers for SE amplifiers not only have to carry the AC power, they are also subjected to magnetisation by the DC anode current, (in a push-pull amplifier the DC magnetisation from the 2 output tubes cancels). The primary inductance is dependant both on the applied AC voltage and the applied DC current.

Transformers for SE amplifiers are equipped with an air-gap in the magnetic circuit to avoid core saturation by the DC current. The optimum air-gap depends on core material and DC current and it is important to choose a transformer that is specified for the DC current in the actual amplifier. Choosing a transformer designed for much higher DC current than what is needed is false economy, such a transformer is un-necessary large and have less performance than a transformer that is designed for just the needed DC current.

Note the difference between saturating current and operating DC-current, saturating current is max current for complete saturation of the transformer, at this current the core is saturated and μ_e and L_p approaches 0, note that it is not possible to operate the transformer at this current.

6.2.2 Interpreting manufacturer data for primary inductance

The problem is that some manufacturers give primary inductance values for high primary AC voltages and others give values for very low AC voltages, due to what has been described above the inductance naturally will be lower for low AC voltages than for higher so the values can not be directly compared.

Some manufacturers as for instance Tango give 2 values of primary inductance, one for small AC voltages and one for high AC voltages, as an example the values for Tango FC-120-5 is 160H and 580H where the higher value is indicated as peak inductance, i.e. at a point where it is at maximum but the low value is measured with an AC signal of 1mW. Without knowing the core material and the μ_e/B curve for it, it is very difficult to recalculate this kind of data for other conditions but at least it is possible to compare Tango transformers with other transformers where L_p is measured at peak μ_e .

6.3 Current imbalance, (for push-pull transformers)

In push-pull transformers the DC magnetisation cancels if the anode current for the 2 tubes are equal, therefore it is important to provide for some sort of means to balance the current if as the case maybe if the tubes are not 100% matched.

Transformers made with EI type lamination usually can withstand some minor current imbalance without air-gap but C-cores and toroidal-type cores are more sensitive for imbalance. Most high quality C-cores are equipped with a minor air-gap to be able to withstand DC-imbalance but toroidal-type cores does not have any air-gap and are therefore much more sensitive to current imbalance than other types.

If there is a current imbalance the primary inductance will be reduced which will be evident as bad low frequency response which also will be worse at low signal level, (when the permeability is lowest). Most high quality manufacturers give a value for max allowed DC-imbalance or give value for the DC-imbalance value where the other parameters are measured.

6.4 Max power or lowest useable frequency

The maximum output power is usually given at a certain frequency where the power has been reduced by 3dB, this is mostly dependant on the primary inductance L_p at the magnetisation given by the power level, if the power level is decreased the inductance is increased but as it is not possible to know at what level of magnetisation the measurements of L_p are made it is difficult to compare data from different manufacturers.

Some manufacturers like Tango instead specifies max power at a certain level of distortion.

6.5 Frequency range or highest useable frequency

The high frequency limit of a transformer is dependant on 2 parameters, leakage inductance and winding capacitance, it is unusual to find values for both these parameters in data sheet which is a pity as it is difficult to compare transformers without knowing both parameters. It is not enough that leakage inductance is low, it also need to be balanced to the capacitance value otherwise the frequency response for high frequencies will not be optimal. The leakage inductance and winding capacitance form a low pass filter and the relation between these 2 parameters decide the response of this filter, for optimum result the filter should ideally have a filter Q of ~ 0.7 , (Butterworth response).

If the leakage inductance and winding capacitance has the wrong relation the high frequency limit can look good on paper but the practical result will not be optimal.

Too high leakage inductance automatically means that the winding capacitance is too low and the result is a high frequency -3dB point that is very high but the attenuation above the -3dB point increases very quickly, this means also that the phase response change quickly and it will be difficult to make the amplifier stable when feedback is used, in some cases there can even be so that the amplitude is increasing at high frequencies and then suddenly drops rapidly.

Too low leakage inductance automatically means that the winding capacitance is too high and the result is that the attenuation at high frequencies is reduced more gradually with an un-necessary too low high -3dB point.

6.6 Insertion loss

Insertion loss can be measured in many different ways that differs between manufacturers, some transformers can be connected in such a way that loss is less dependent on load impedance, (Lundahl); normally loss is lowest to the output with the highest impedance.

Manufacturer	Tango	Plitron	Lundahl	ASV
Lp, max	At max μ_e	At 250V, 60Hz, (max μ_e ?)	At max power	At 230V, 50Hz, (max μ_e ?)
Lp low level	At 1mW	No	No	No
Lp at current imbalance	Yes, actual DC current value is depending on transformer type	No	No	No
Bandwidth	Yes, at low level, can be used to calculate value of Lsc	Yes, but no conditions given	Yes, but no conditions given	Yes, but no conditions given
Lsc	No	Yes	Yes	Yes
Max power condition	Distortion < 1% 3 rd order at 30Hz	?	At -3dB / 30Hz	?
Low frequency limit, conditions	At 4Vp-p, Rg = 0.5Zp	?	At full power only	At 1mW, Rg unknown

Loss	To 16 ohm output	?	?	?
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7 Designing you own output transformer

Designing you own output transformer can be a rewarding experience but I must warn you that it also means a lot of hard manual work, if you value your spare time in money it is probably a waste of money and time to design your own transformer. It takes quite long time to wind a transformer using DIY equipment, the winding machines that commercial manufacturers uses make the work much easier.

7.1 Choice of tools

What is needed is basically a hand cranked hand drill that you set up horizontally in a vice. You will also need a square piece of wood that fits snugly inside the bobbin. Drill a hole trough the centre of the wood piece and mount a long screw trough the hole secured with washers and a nut. The end of the screw is placed in the chuck of the drill.

It is possible to count the turns by hand but it is very easy to make a mistake so it therefore pays off to set up some sort of automatic rev counter if it can be arranged.

7.2 Choice of materials

The most important material is of course the core, which could be an EI type core or a C-core. Old power transformers can be used, the metal in these transformers are usually plain silicon iron which gives acceptable results, see information about the Williamson transformer described in chapter that was design using ordinary silicon iron. The best EI cores have thin laminations, preferably 0.35mm or less. Even better are C-type cores and they are not so difficult to find these days.

Enamelled copper-wire is not difficult to source but is getting more expensive.

Insulation paper can be difficult to get hold of but graphical and artist shops have waxed paper that is good as insulation. Insulation between layers in the same side (primary or secondary) should be paper with typical thickness 0.05mm. Insulation between primary and secondary sections should be thicker in order to withstand the isolation typically 0.3mm is enough. On of the best isolation paper that exists is the one found in old paper capacitors but these are hard to found nowadays.

7.3 Initial dimensioning

First choice is if the transformer should be used in a SE amplifier or push-pull. In SE amplifier the core is subjected to DC magnetisation and therefore need an air-gap and a larger core than a push-pull transformer.

Some initial data is needed in order to start calculations.

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- Primary load impedance, Z_p
- Secondary impedance, Z_s
- AC Power, P
- Acceptable distortion level
- Lowest frequency at full power, F_{min}
- Highest frequency at $-3dB$, F_{high}
- Max DC current

Choose reasonable values for these parameters, it is unlikely that you will be able to make a transformer that is equal to the very best on the market but I know that it is possible to make very good transformers as DIY.

My recommendation is to start design the transformer for power level, low frequency limit, distortion and DC current and then calculate what the high frequency response will be. If you are not satisfied with the high frequency performance you need to compromise by allowing a higher F_{min} or limit the max power.

Please note the importance of distortion that normally always determines the primary turns and therefore the transformer size.

8 Units used in magnetic formulas

Designation	Unit	Description
Lp	H	Primary winding inductance
Llp	H	Primary leakage inductance
Ls	H	Secondary winding inductance
Lls	H	Secondary leakage inductance
Rp	Ohm	Primary resistance
Rg	Ohm	Primary generator impedance
Rs	Ohm	Secondary resistance
RI	Ohm	Secondary load impedance
Zp	Ohm	Primary load impedance = $a^2 \times RI$
Np	Dimensionless	Primary turns
Ns	Dimensionless	Secondary turns
μ	Dimensionless	Permeability
μ_0		Permeability for air
μ_e	Dimensionless	Effective permeability
Ac	mm ²	Core Area
S	A/mm ²	Current density
MPL	mm	Magnetic path length trough core
La	mm	Magnetic path length trough air, air-gap
MLT	m	Mean Length per Turn
B	Gauss	Magnetic flux density
H	Oersteds	Magnetic field strength
Φ	Maxwell	Magnetic flux
F	Hz	Frequency
VpAC	V	Primary AC voltage
VsAC	V	Secondary AC voltage
Xm	Ohm	Primary reactance
α	Dimensionless	Turns ratio, Np/Ns

9 Design of push-pull transformers, (no air-gap)

Notes: Distortion level and Fmin give value of primary inductance; usually distortion is of more importance.

9.1 Needed in-data

Primary load impedance, Zp

Secondary impedance, Zs

Power, P

Allowable distortion level, %

Lowest frequency at full power –3dB, Fmin

Highest frequency at –3dB, Fhigh

Bmax for chosen core material

9.2 Calculate transformation ratio α

$$\alpha = \sqrt{\frac{Zp}{Zs}}$$

9.3 Calculate required core area

$Ac_{14000} = 900 * \sqrt{\frac{P}{F \text{ min}}}$ mm², for Bmax =14000 Gauss, for other degree of

magnetisation use $Ac = Ac_{14000} * \sqrt{\frac{14000}{B \text{ max}}}$

9.4 Calculate required min primary inductance Lp

Calculate $R' \text{ par} = \frac{(R1 * R2 * \alpha^2)}{(R1 + R2 * \alpha^2)}$, where $R1 = Rg + Rp$, and $R2 = Rl + Rs$

As a starting point assume $Rs = \frac{Rp}{\alpha^2} \approx 0.05Rl$, this gives a copper efficiency of 91%

Calculate required $Lp = \frac{R' \text{ par}}{2\pi f}$

9.5 Calculating allowable leakage inductance

Calculate $R' \text{ se} = R1 + R2 * \alpha^2$

$$Llp = \frac{R'se}{2 * \pi * Fhigh}$$

9.6 Check for distortion at a given frequency f

Assume Bm = 5000

$$\text{Calculate } Np = \frac{Vrms * 10^{10}}{4.44 * Bac * f * Ac}$$

$$\text{Calculate } Lpd = \frac{1.257 * \mu e * N^2 * Ac * 10^{-9}}{Lc}; \text{ use } \mu e \text{ from table in 5.5}$$

$$\text{Calculate } Xm = 2 * \pi * f * Lpd$$

$$\text{Calculate harmonic distortion from: } \frac{Eh}{Ef} = \frac{Ih}{If} * \left(\frac{R' par}{Xm} \right) * \left[1 - \left(\frac{R' par}{4 * Xm} \right) \right]$$

$\frac{Ih}{If}$ Values for 4% FeSi

Bm	Ih 3 rd order	Ih 5 th order
100	4	1.0
500	7	1.5
1000	9	2.0
3000	15	2.5
5000	20	3.0
10000	30	5.0

9.7 Calculate secondary number of turns

$$Ns = Np * \sqrt{\frac{Rl}{Zp}}$$

9.8 Check that the wire fits the given space

Calculate the Mean Length per Turn in meter

Calculate total length for primary and secondary

$$Ltotp = Np * MLT$$

$$Ltots = Ns * MLT$$

Calculate wire area for primary wire $A_p = 0.017 * \frac{L_{totp}}{R_p}$ mm² Calculate wire area for secondary wire $A_s = 0.017 * \frac{L_{tots}}{R_s}$ mm²

Select wire for primary and secondary windings; allow 3A/mm² for ordinary enamelled copper wire, if thick enough wire doesn't fit on the available space a new calculation has to be started from chapter 9.6

Wire diameter is calculated from $D = \sqrt{\frac{A * 4}{\pi}}$

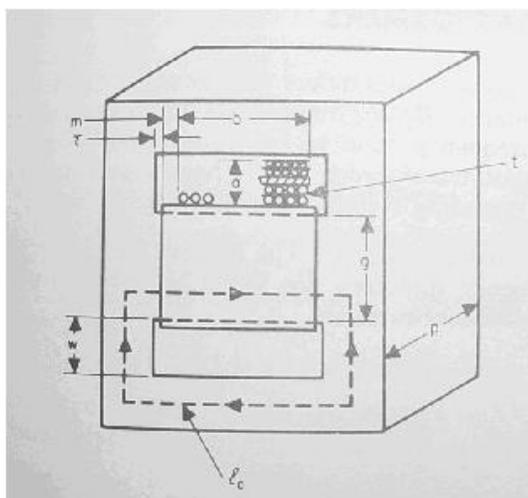
Calculate the number of primary and secondary layers

Calculate if the wire fits in the available space including insulation

9.9 Check value of leakage inductance

Formula for interleaved primary and secondary windings

$$L_{lp} = 0.4 * N_p^2 * MLT * \frac{(2 * n * t + a)}{(n^2 * b * 10^9)}$$



Physical dimensions related to calculation of leakage inductance

Where n is the number of section interfaces, as an example a transformer having 5 primary sections and 4 secondary sections have 8 section interfaces.

a is the total thickness of the coils in mm

t is the thickness of isolation between layers in mm

b is the width of the winding in mm

10 Design of SE transformers, (with air-gap)

Designing transformers for Single Ended amplifiers where the core is subjected to both DC and AC magnetisation is quite a bit more difficult than for push-pull transformers.

The first choice is the degree of DC magnetisation, most common is to use a value that is half of Bmax, which is typically ~14000 - 16000 for silicon iron, this means that max AC magnetisation will be half of this, or 7000 – 8000 Gauss for silicon iron

10.1 Needed in-data

Primary load impedance, Zp

Secondary impedance, Zs

AC Power, P

Lowest frequency at full power, Fmin

Highest frequency at –3dB, Fhigh

DC current

10.2 Calculate required core area

$A_{c_{14000}} = 1270 * \sqrt{\frac{P}{F_{\min}}} \text{ mm}^2$, for Bmax =14000 Gauss, for other degree of magnetisation use $A_c = A_{c_{14000}} * \sqrt{\frac{14000}{B_{\max}}}$

10.3 Calculate required min primary inductance Lp

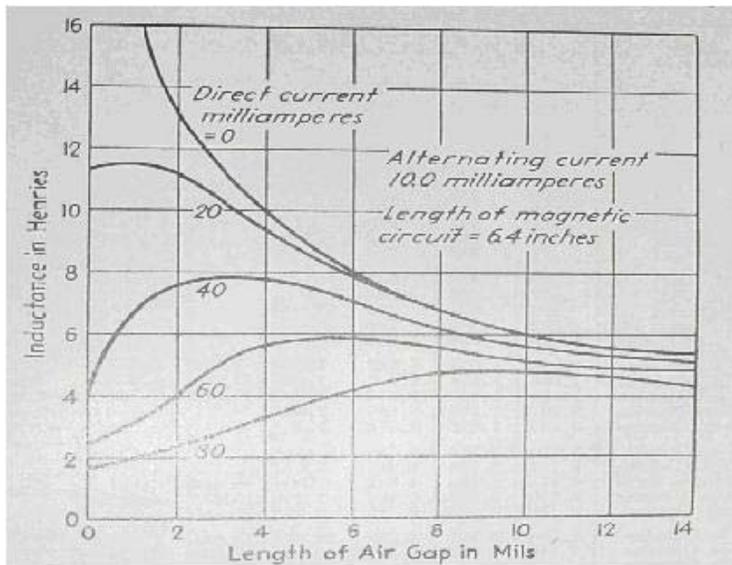
Calculate $R'_{par} = \frac{(R1 * R2 * \alpha^2)}{(R1 + R2 * \alpha^2)}$, where $R1 = Rg + Rp$, and $R2 = Rl + Rs$

As a starting point assume $R_s = \frac{Rp}{\alpha^2} \approx 0.05Rl$, this gives a copper efficiency of 91%

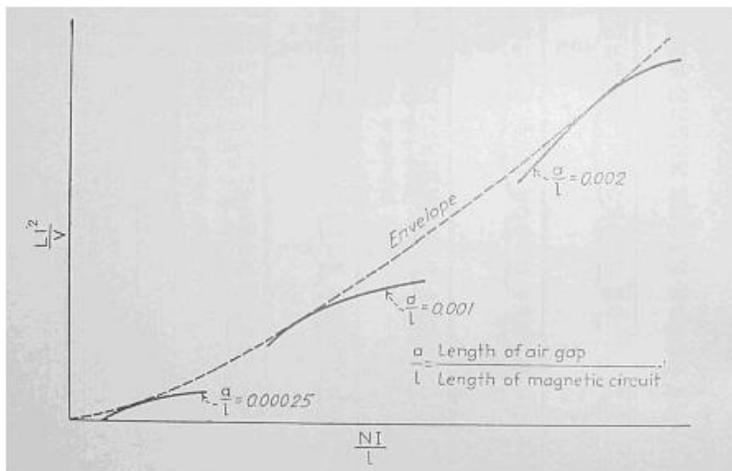
Calculate required $L_p = \frac{R'_{par}}{2\pi f}$

10.4 Determine air-gap

There is a particular air-gap for which the incremental or AC inductance reaches a maximum when the core material and dimensions, the number of turns, and the DC magnetising current are fixed. As the DC magnetising current is increased, the optimum air-gap becomes longer and the corresponding incremental AC inductance less. The behaviour in a typical case is shown by the figure.



This best length of air-gap can be obtained by plotting curves of $\frac{L \cdot I^2}{V}$ as a function of $\frac{N \cdot I}{MPL}$ for various percentage air-gap lengths, as shown by the figure below, where L is the incremental AC inductance, I is the direct current, V the volume of the core, N the number of turns, and MPL the length of the magnetic circuit.



10.5 Calculate number of turns for primary

10.5.1 Calculate the effective permeability of the core with the given air-gap

$$\mu_e = \frac{\mu}{\left(1 + \mu \left(\frac{La}{MPL}\right)\right)}$$

10.5.2 Calculate the number of turns given μ_e

$$N_p = \frac{B_{\max} * MPL}{25.14 * \mu_e}$$

10.6 Calculate primary inductance L_p

$$L_p = \frac{1.257 * \mu_e * A_c * 10^{-8}}{MPL}$$

Check if this value is reasonable, otherwise select a bigger or smaller core and go back to 10.4

10.7 Calculate B_{\max}

$$B_{AC} = \frac{V_{RMS} * 10^{10}}{4.44 * N_p * f * A_c}$$

This value should be close to half of B_{\max} otherwise select a bigger or smaller core and go back to 10.4

10.8 Calculate secondary number of turns

$$N_s = N_p * \sqrt{\frac{R_l}{Z_p}}$$

10.9 Check that the wire fits the given space

Calculate the Mean Length per Turn, MLT in meter

Calculate total length for primary and secondary

$$L_{totp} = N_p * MLT$$

$$L_{tots} = N_s * MLT$$

Calculate wire area for primary wire $A_p = 0.017 * \frac{L_{totp}}{R_p}$ Calculate wire area

for secondary wire $A_s = 0.017 * \frac{L_{tots}}{R_s}$

Select wire for primary and secondary windings allow 3A/mm² for ordinary enamelled copper wire if thick enough wire doesn't fit on the available space a new calculation has to be started from chapter 10.4

$$\text{Wire diameter is calculated from } D = \sqrt{\frac{A * 4}{\pi}}$$

Calculate the number of primary and secondary layers

Calculate if the wire fits in the available space including insulation, a good transformer has a fill factor of 85% that is the windings take up 85% of the available space

10.10 Calculating allowable leakage inductance

Calculate $R'_{se} = R1 + R2 * \alpha^2$

$$L_{scp} = \frac{R'_{se}}{2 * \pi * F_{high}} \text{ H}$$

10.11 Check value of leakage inductance

Note this formula is for a transformer with interleaved primary and secondary windings.

$$L_{lp} = 0.4 * N_p^2 * MLT * \frac{(2 * n * c + a)}{(n^2 * b * 10^9)}, \text{ all dimensions in mm}$$

Where n is number of section interfaces, as an example a transformer having 5 primary sections and 4 secondary section have 8 section interfaces.

a is the total thickness of the coils

c is the thickness of isolation between layers

b is the width of the winding

11 The Williamson transformer

The Williamson amplifier designed by D.T.N Williamson is a milestone in audio amplifier design. Williamson was employed by The GE Valve Company as an engineer and he designed the amplifier partly because of his own interest but also as a way for the GE Valve Company to promote their new KT66 Beam tetrode.

The unique thing about the Williamson amplifier is that it was the first time an amplifier was designed using what could be seen even today as modern design methods. Triode coupled beam tetrodes were used together with a well designed input and driver stage, feedback was also applied in a controlled manner achieving a bandwidth of 20 – 20 kHz within 0.2dB and a distortion level of <0.1% at up to 15W output power.

The Williamson amplifier has been subjected to criticism over the years but in most cases this is due to misunderstanding of the original circuit function or because many people have modified the original circuit in order to "improve" it.

The most common "improvements" are using an output transformer other than the one specified, ultra-linear coupling of the output stage, change of tubes in the driver stage from original L63's to other tubes without modification of other circuit values or change of output tubes from original KT66's to 807's or other tube. Most of these changes don't offer any improvement of the original design; on the contrary most of these modifications will increase distortion, reduce bandwidth or introduce instability compared to the original circuit.

The Williamson amplifier in its original form with the specified circuit values, tubes and output transformer is still a very good amplifier even when compared to newer designs be it tube or transistor equipped.

The only basic thing I think could be improved in the basic design is stability at low and high frequencies, in the original Williamson amplifier the phase margin is quite low ~30 degrees which is acceptable but I feel that a higher degree of phase margin is desired and is not difficult to achieve by subtle modifications in a Williamson amplifier without affecting any other parameters.

The transformer specified by Williamson was said to be designed in a new way compared to many others, that is not quite thru, there had been other companies and designers thinking about the same idea and the basic ideas are for instance described in "Radio engineers handbook" by F.E. Terman with references to other works as early as 1928. However it is mainly not the details that are imaginative in the Williamson amplifier but the whole concept.

One however rather unique design concept with the transformer specified by Williamson is that it was designed to a certain distortion level, this was not usual at the time but instead output transformers where normally designed to pass a certain power level at a certain low frequency limit.

As can be seen by the formulas in chapter 9 a transformer can either be designed for low frequency limit or for a specified degree of distortion, either of these parameters determine the number of primary turns and the core size. In the majority of cases designing for low distortion determine the size of the transformer and not the low frequency limit, this is something that even today is not recognised by most transformer manufacturers, the only exception I really have found is Tango.

So, the Williamson transformer is big mainly not because it was designed a long time ago but because it was designed for low distortion!

The transformer itself is wound on a EI core similar to EI125 e.g. the transformer is 125mm wide, the thickness of the core was 1.75" ~44.5mm. The material is super Silcor which is actually ordinary silicon iron with 4% silicon, the used laminations where 0.01" thick.

The transformer is wined in 2 parts side by side, each part consist of 5 primary sections and 4 secondary sections. Each primary section consists of 5 layers with 88 turns of 0.25mm enamelled copper wire in each layer. Each secondary section consists of 2 layers with 29 turns of 0.9mm enamelled copper wire in each layer. Each layer is insulated with paper 0.05mm thick and between primary and secondary sections are 3 layers of paper 0.13mm thick.

The transformer has the following data:

Primary inductance	100H at small signal
Leakage inductance	<22mH
Distortion at 30Hz and 15W	<1%
Bandwidth at 15W –3dB	30 Hz to 60 kHz

This data is still comparable with data of many transformers of today; only the more expensive models from Tango, Tamura, Lundahl and some others show significantly better data.

12 References

It is not easy to find literature containing all needed formulas for transformer calculations; I have therefore collected information from various sources, some of the most important are mentioned here:

Private unpublished papers by Olof Beijner, (my father)

“Radio Engineers Handbook” by F.E. Terman

“Reference Data For radio Engineers” published by ITT

“The Williamson Amplifier” article series from Wireless World 1947