Secrets of Output Transformers

By Menno van der Veen

Introduction

In this article I intend to tell something about output transformers (OPTs). I want to explain to the readers how to select an optimal OPT for their special application. I will introduce the challenging possibilities of the new “Specialist” toroidal OPTs. Formula’s will not be used in this explanation. I will explain with words and point to my books, lab reports and AES pre prints for those who love doing complex calculations. There we go.

SE- and Push-Pull- Output Transformers

In tube amplifiers you need an OPT because the voltages in the tube amplifier are too great for your loudspeaker, while the current capability of the tubes is too small to drive your speaker correctly. There exist fabulous Output Transformer-less amplifier designs (OTL) but most tube amps use output transformers. The function of an OPT is to lower the high voltage to safe values and to multiply the weak tube currents into larger values. This action is performed by winding different amounts of turns on the incoming (primary) and outgoing (secondary) side of the OPT. The turns ratio between primary and secondary is the major tool performing this job.

All the output transformers can be divided into two groups. The transformers for Single Ended (SE) amplifiers and the transformers for push-pull amplifiers. The major difference between these two is that in SE-OPTs the quiescent current of the power triode is not compensated in the transformer core, while in push-pull transformers the quiescent currents of the two push-pull power tubes cancel each other out in the core of the OPT. This means that an SE transformer must be constructed differently from a push-pull type. In general one can say that a SE-transformer includes a gap in the core to deal with the quiescent current while the push-pull version has a closed core with almost no gap in it. This means: when you own a very good push-pull OPT you can’t apply it in a SE-amplifier!

Impedances

Suppose you want to select an OPT for a special design. Suppose that we are dealing with a push-pull amplifier. Somewhere in the design notes you should find the primary impedance (Z_{aa}) for optimal loading of the power tubes. Let’s imagine a design with a primary impedance of 3300 Ohms. On the secondary side you wish to connect a 4 or an 8 Ohms loudspeaker. I have standardised my toroidal designs to a 5 Ohms secondary, but very often the 4 plus 8 Ohms connections are found. Suppose for now that you have found a transformer with a primary impedance of 4000 Ohms and secondaries at 4 and 8 Ohms. Can you use this transformer for your special design where Z_{aa} should equal 3300 Ohms? The answer is yes, you only have to perform a minor calculation to see how.

In your transformer you have an impedance ratio of 4000/4 = 1000. Now suppose that you don’t apply a 4 Ohms loudspeaker but a 3.3 Ohms version, then with this impedance ratio of 1000 you get a primary impedance of 3300 Ohms. When you use the 8 Ohms secondary connection, your impedance ratio is 4000/8 = 500. To get a primary impedance of 3300 Ohm you should apply a loudspeaker with an impedance of 3300/500 = 6.6 Ohms.

These examples deliver the following important rule: “the impedance ratio of the OPT combined with the impedance of the loudspeaker delivers the primary impedance”.

Another example: suppose you have an SE-OPT with a primary impedance Z_a = 2500 Ohms.

Secondary you have a 4 Ohms connection. The impedance ratio is 2500/4 = 625. Now suppose that you wish to build a 300B SE-amplifier with a primary impedance of 3500 Ohms. What speaker should you connect? The answer is: 3500/625 = 5.6 Ohms.

Every one knows that the impedance of a loudspeaker is frequency dependent, meaning that at each frequency the impedance has a different value. Therefore loudspeaker manufacturers give a mean impedance value. The consequence of this is that you never can calculate exactly the value of the primary impedance. Just try to be close to the primary and secondary impedances intended in the design, but don’t worry for deviations up to about 20 %. These criteria will make your selection of an output transformer much easier.

Power Capability and Losses

The output transformer must be able to handle the output power without major losses and distortions, at the intended frequency range. This is a rather difficult topic because not all manufacturers deliver all the information you need to judge whether the OPT is applicable or not. What you need is the following: “at which lowest frequency the transformer can handle its nominal power”? I give an example: suppose you select an OPT which can handle 50 Watts at 30 Hz. Then this transformer can handle 50/2 = 25 Watt at 30/1.414 = 21.2 Hz. Or the transformer can handle 50*2 = 100 Watt at 30*1.414 = 42.4 Hz.

The rule behind all this is: “the power capability doubles when the frequency is a factor 1.414 larger. The power capability halves when the lowest frequency is divided by 1.414 (square root 2)”.

But what to do when the manufacturer only tells you that you buy a 100 Watt transformer without mentioning the lowest nominal power frequency? To be honest: the lack of information makes you ‘blind’ and you don’t know how the behaviour of this transformer will be at low frequencies. The lower the frequency, the more the core of the OPT gets saturated and you only can guess at what frequency severe distortions will start. The only thing you should count on is the good name of the manufacturer, expecting that he is knowing what he is doing. I plead however, for power specifications to be delivered with each OPT combined with the lowest frequency. It will help you selecting the optimal OPT for your application.

Now let us look at the losses in an OPT. All the magnet wire turns of the OPT have a resistance. The currents of the tubes are partly converted into heat in this internal resistance and therefore you loose power. This is expressed in the "Insertion Loss" which you find in the specifications of the OPT. Let me give an example: suppose an I-loss of 0.3 dB, how much power is lost in heat in the transformer? Now take your calculator and calculate: 0.3/10 = 0.03, calculate -0.03 with the inverse log-function (10 to the power of [-0.03]) resulting in 0.933. This results means that 93.3 % of the output power is converted into music while 100-93.3 = 6.7 % is converted into heat. This knowledge does not enable you to bake an egg on the transformer, so a more general rule will give better information: "insertion losses smaller than 0.3 dB in an OPT indicate an acceptable heat loss without causing major difficulties".

Low Frequency Range and DC-Imbalance

The calculation of the frequency range of an OPT is very complex. You find all the information and details in my AES pre print 3887: "Theory and Practice of Wide Bandwidth Toroidal Output Transformers", to be ordered at the AES-headquarters and included in this data book. I now only will deal with the frequency range at the low frequency side. The most important quantity determining this range is the primary inductance L_p (its value is given in H = Henry). The larger L_p the better the low frequency response of the transformer. To make L_p large you need a lot of magnet wire turns around the core and you need to use a large core. A second factor determining the low frequency range is the primary impedance of the OPT in parallel with the plate resistances of the output tubes. The smaller the plate resistances and primary impedance the wider the frequency range at the low frequency side. Select power tubes with a low plate resistance (like triodes) for a good bass response with very little distortion combined with OPT's with a large L_p value. (See for a more detailed study my recent article in Glass Audio 5/97: "Measuring Output Transformer Performance", starting at page 20 (this article is included in this data book)).

However, the larger you make L_p , the more sensitive the OPT becomes for an imbalance of the quiescent currents of the power tubes in a push-pull amplifier design. In practice this means: when you use high quality OPT's with good bass response and a large primary inductance, you should pay special attention to carefully balancing the quiescent currents of the power tubes. Whether you use my toroidal designs or EI-designs or C-core designs, this is a general rule for large primary inductance OPT designs. If you don't balance your quiescent currents carefully, your maximum power capability at low frequencies gets less and there the distortions become larger.

High Frequency Range

At the high frequency side, two internal quantities of the transformer limit the high frequencies. These are: the effective internal capacitance between the windings (C_{ip}) and the leakage inductance of the transformer (L_{sp}). The leakage is caused by the simple fact that not all the magnetic field lines are captured in the core. Some leave the core and are outside the transformer. In this aspect the toroidal transformers show very good specifications, because the round shaped core captures almost all the field lines, resulting in very small leakage inductances. The smaller the leakage, the wider the frequency range.

The influence of the internal capacitance is the same: the smaller the internal capacitance, the wider the high frequency range. A transformer designer therefore has to find an optimal balance between the leakage, the capacitance and the tubes and impedances used to create an optimal frequency range. I have discussed this in detail in my 3887 AES pre print.

Now some rules:

"the smaller the plate resistances of the tubes, the wider the frequency range".

"When the balance between L_{sp} and C_{ip} is not correct, square wave overshoot will occur (incorrect Q-factor)".

"When both L_{sp} and C_{ip} are large, the high frequency range gets limited and this will result in differential phase distortions" (meaning that the frequency components of a complex tone, or of the pulse like sounds in music, will be time-shifted towards each other, resulting in a distorted tone envelope, detectable by the ear due to its a-linear behaviour).

Let me summarise this as follows: it is up to the transformer designer not only to create a wide frequency range, but to tune the high frequency behaviour with the correct Q-factor (somewhere between 0.5 and 0.7). In that case no square wave overshoot will occur and the differential phase distortion will be minimal. Look into the specifications of the manufacturer to find more details about the high frequency tuning of his designs. I have optimised my toroidal designs for a very wide frequency range, in order to be prepared for the new digital developments with sampling rates now up to 194 kHz, but who knows what the near future will bring.

Special Configurations and New Adventures

Recently I finalised a study and research about special coupling techniques between an OPT and power tubes. The results of this research can be found in my newest AES pre print 4643: "Modelling Power Tubes and their Interaction with Output Transformers", to be ordered at AES headquarters.

My basic question was: "how can I couple power tubes optimal to an output transformer"? In order to answer this simple question I first had to design a mathematical model describing the behaviour of power tubes. Fortunately many others (like for instance the pioneers Scott Reynolds and Norman Koren) already had studied this subject and I only had to add a very small extension to their models to be able to model pentode power tubes rather accurate.

My next important step was the understanding that there are many ways to connect power tubes to output transformers. I only mention a few possibilities: Pentode push-pull, Ultra Linear, Triode push-pull, cathode feedback, cathode out, and so on.

I discovered that it is possible to bring all these various coupling techniques into one general model by means of the introduction of the screen grid feedback ratio X and the introduction of the cathode feedback ratio’. The following figure clearly shows a lot of different coupling methods between the push-pull power tubes and the OPT.

To investigate all these special coupling methods, I designed a new range of toroidal OPT’s: the “Specialist Range”. These new transformers contain special windings for the application of selectable cathode and screen grid feedback. The major time consuming element in the designing of these new toroidal transformers was the demand that the amplifiers should be absolutely stable, not oscillating, and optimised in power, frequency range and damping factor behaviour. During my research and the development of the new OPT’s I discovered two brand new circuits (numbers 5 and 7) which are under my registration and copyright For details of this new research, refer to other articles in this data book.

The circuits 5 (Super Pentode) and 7 (Super Triode) both show very special qualities not seen before by me in push-pull amps. For instance: circuit 5 delivers amazingly large output powers (80 Watt with 2 x EL34 at 450-470 V supply), while circuit 7 delivers extreme small distortions (harmonic as well as intermodulation) and a damping factor surpassing triode amplifiers. In all this I noticed (and calculated) that especially the quiescent current per power tube is a major tool in creating minimal distortions (while not influencing the maximum output power). The new toroidal “specialist” transformers are available now for any one to perform his/her private tests with these new amplifier possibilities.

Note:

Super Pentode and Super Triode: Names and principles are registered by the author and are subject to European Union and International Copyright Laws. Licensing enquires for reproduction of and manufacture for trade sale should be directed to Menno van der Veen

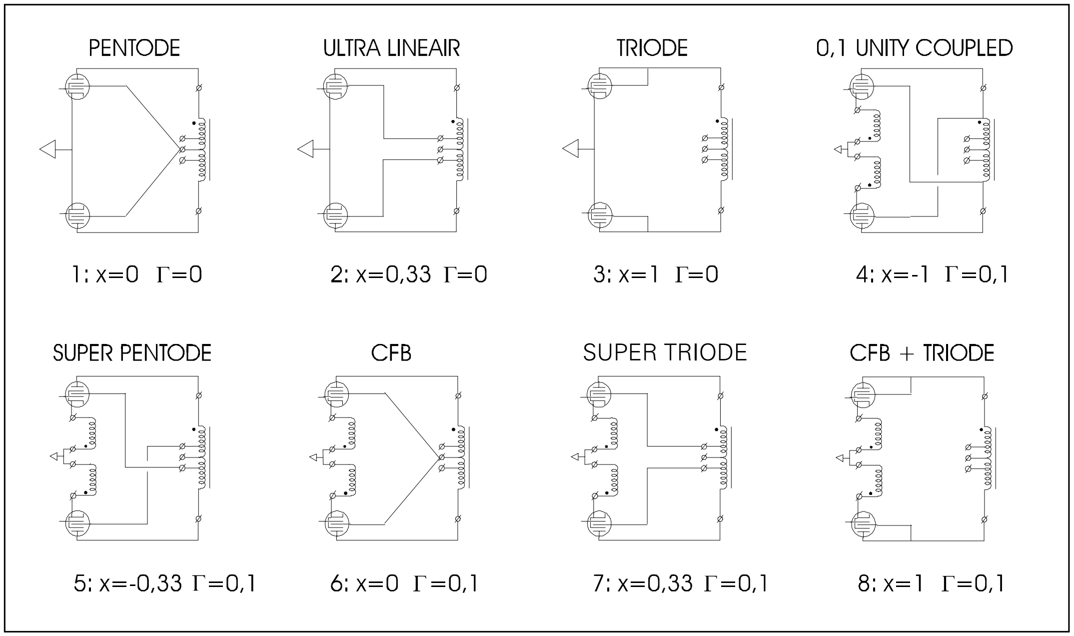

FIGURE: Eight amplifier configurations.