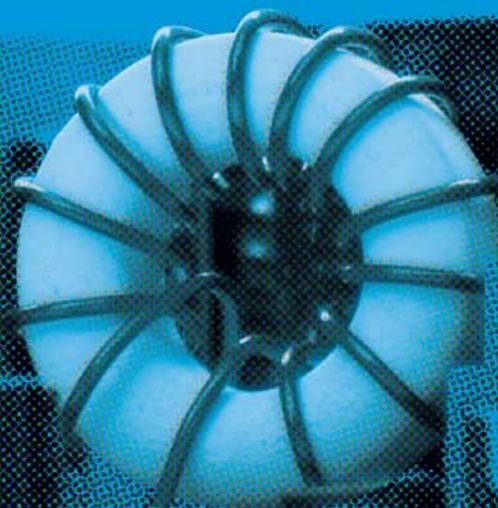
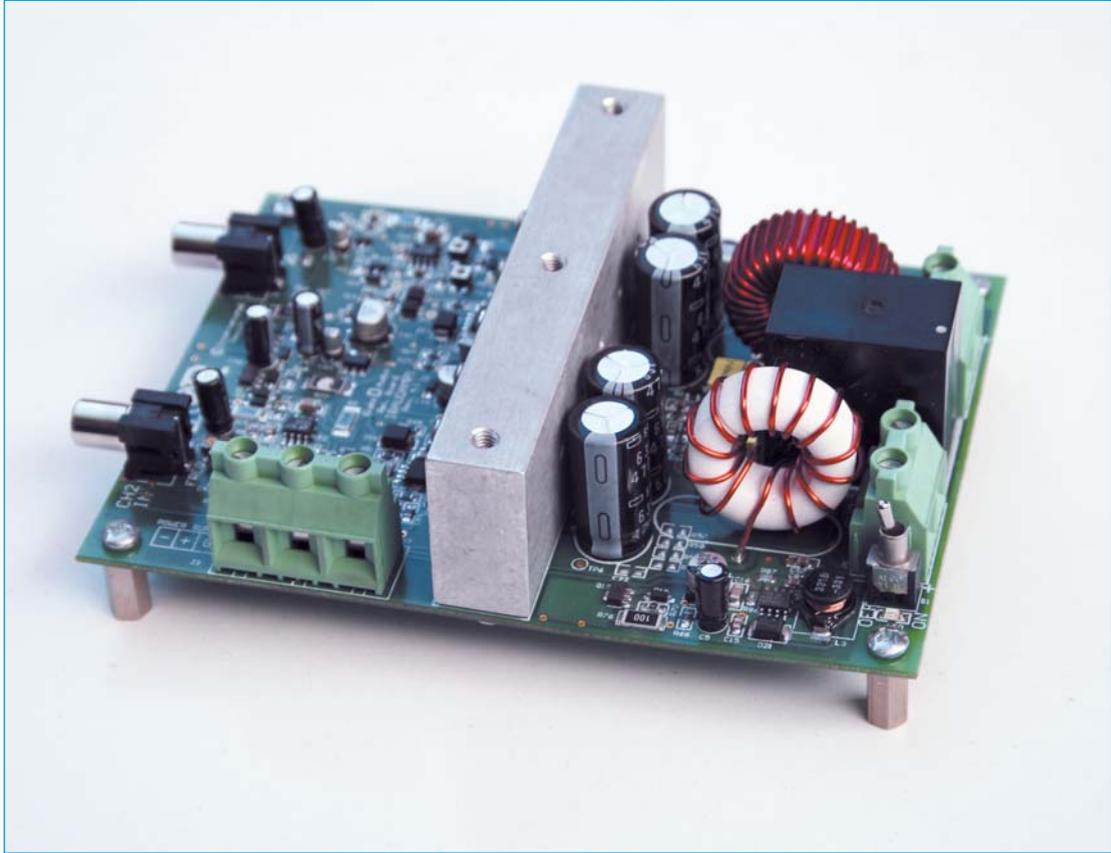


***Class D audio amplifier
with Ferroxcube
gapped toroid output filter***

Application Note





Class D audio amplifier with Ferroxcube gapped toroid output filter

The concept of a Class D amplifier has been around for a long time, however only fairly recently have they become commonly used in consumer applications. Due to improvements in the speed, power capacity and efficiency of modern semiconductor devices, applications using Class D amplifiers have become affordable for the common person. The main benefit of this kind of amplifier is the efficiency, the theoretical maximum efficiency of a class D design is 100%, and over 90% is achieved in practice.

Other benefits of these amplifiers are the reduction in consumption, their smaller size and the lower weight. Their advantages are obvious in low power battery operated personal audio players and laptop computers. However they are also progressively displacing more traditional linear designs in mainstream applications such as home entertainment systems, automotive sound systems, and professional installations where high quality audio is important.

Audio Amplifiers

An electronic amplifier is a device for increasing the current, voltage or power of a signal. It does this, by taking power from a power supply and controlling the output to match the

input signal shape but with larger amplitude. An audio amplifier is specially designed for reproducing audio frequencies.

Amplifier circuits are classified as A, B, AB and C for analog designs, and class D and E for switching devices. For the analog classes, each type defines which proportion of the input signal cycle is used to switch on the amplifying device:

Class A → 100%

Class AB → Between 50% and 100%

Class B → 50%

Class C → less than 50%

The letter D used to designate the class D amplifier, is simply the next letter after the C, and does not stand for digital. Class D and E are sometimes mistakenly defined as digital because the output waveform superficially resembles a pulse train of digital symbols.

Class D amplifiers

A class D amplifier is basically a switching amplifier or pulse width modulator (PWM from now on) amplifier. In this kind of amplifier all power devices are operated in on/off mode, reducing the power losses in the output devices significantly.

Class D amplifiers can be categorised into two topologies; half bridge and full

bridge configuration. Each topology has pros and cons. In brief, a half bridge is potentially simpler, while a full bridge is better in audio performance. The full bridge topology requires two half-bridge amplifiers, and thus more components.

A Class D amplifier works in the same way as a PWM power supply, except that the reference signal is the audio wave instead of the accurate voltage reference.

Let's start with an assumption that the input signal is a standard audio line level signal. This audio line level signal is sinusoidal with a frequency ranging from 20 Hz to 20KHz. This signal is compared with a high frequency triangle or sawtooth waveform to create the PWM signal. The input signal is converted to a sequence of pulses whose averaged value is directly proportional to the amplitude of the signal at that time. The frequency of the pulses is typically ten or more times the highest frequency of interest in the input signal.

This PWM signal is then used to drive the power stage, creating the amplified digital signal, and finally a low pass filter is applied to the signal to filter out the PWM carrier frequency and retrieve the sinusoidal audio signal. The resulting filtered signal is then an amplified replica of the input.

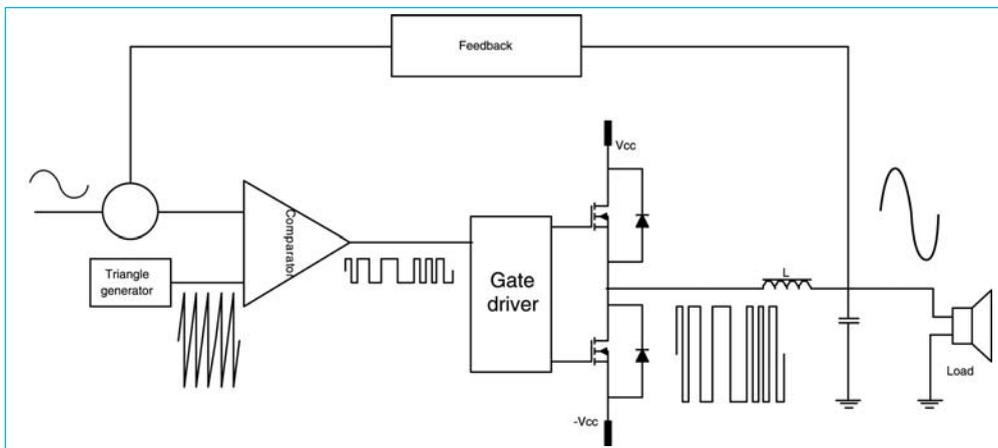


Figure 1: Block diagram of a Class D audio amplifier

CLASS D Audio Power Amplifier with GAPPED FERRITES

One of the most important parts in a class D, audio power amplifier is the output filter. The overall efficiency, reliability and audio performance depends on it. A reference circuit has been modified in order to substitute an inductor by a gapped ferrite. This component is designed to behave with the same performance as the first one.

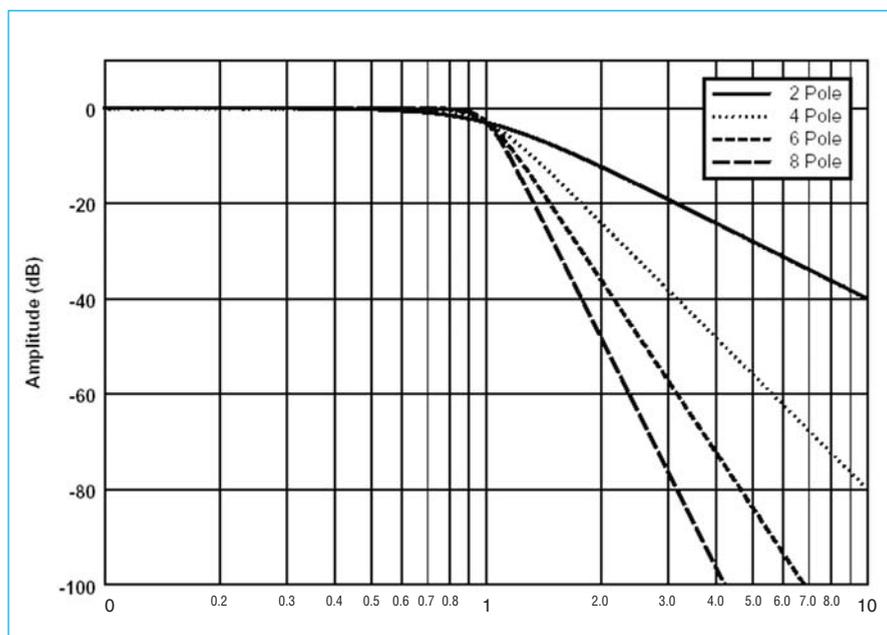
Output Filter Design

The overall efficiency, reliability and audio performance depend on the quality and linearity of the output filter. The main goal of the output filter is attenuation of the high frequency switching component of the class D amplifier while preserving the signals in the audio band.

The order of the filter determines how many poles exist at the same frequency, with each order increasing the attenuation above the cut-off frequen-

cy by -20dB per decade. The switching frequency of the amplifier can influence the choice of the filter order, the higher the f_s , the lower the order required to achieve a given attenuation within a specified passband. This would seem to dictate the use of the highest switching frequency possible. The trade-off is that increasing f_s increases the switching losses and the EMI, thus decreasing the efficiency of the amplifier.

Figure 2: Example of the transfer function of a low pass filter over normalized frequency (f/f_c). Several order filters are shown.



A second order LC filter is the common approach, as it is lossless and has a -40dB/decade slope, allowing for a reasonable rejection of the carrier if the parameters of the filter and the switching frequency itself are properly designed.

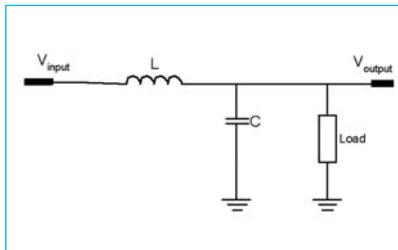


Figure 3: Second order low pass filter structure.

The first thing to do is to design the transfer function for the filter. Usually, a Butterworth or similar frequency response is chosen, with a cut-off frequency slightly above the audio band (30-60KHz). Have in mind that one of the design parameters is the termination load, that is, the speaker impedance. Usually, a typical 4 or 8 ohm resistor is assumed, but that would produce variations in the measured frequency response in presence of different speakers. That must be compen-

sated for by means of proper feedback network design. Some manufacturers simply leave it that way, so the response is strongly dependent on the load. Surely a non-desirable situation.

More information about designing the output filter as a function of the cut off frequency and load impedance is presented in annex 2.

The output inductor withstands the whole output current without saturation, as well as keeps the energy for the off cycle, as in any non-isolated switching converter (Class-D half bridge design is in fact analogous to a buck converter, its reference voltage being the audio signal).

The ideal inductor (in terms of linearity) is an air-core one, but the size and number of turns required for typical Class-D operation makes it impractical, so a core has to be used in order to reduce turns count and also provide a confined magnetic field that reduces radiated EMI. It can be use either powder cores or ferrite cores. Ferrite cores, must have a “gap” where energy is stored. Wire size should also be carefully chosen to keep DC and AC losses low (requiring thick wire).

Magnetic core of the output filter

The linearity of the filter versus frequency and output power strongly influences the performance of the amplifier and quality of the audio signal. Therefore, care has to be taken in order to select the optimal magnetic core at a reasonable cost.

Iron powder cores are the cheapest solution, but the switching frequency (several hundred kilohertz) is too high to make them suitable for this application.

Powder alloy cores are widely used, mainly because they are very popular as output chokes in DC/DC converters and SMPS. The drawback is that the saturation curve is not flat, but with a constant slope drop. To overcome this problem the designer has to over specify the product in the sense that only a small region of the saturation curve is used. Losses at high frequencies are also a thread, implying the use of low permeability materials wound with some 30 to 50 turns.

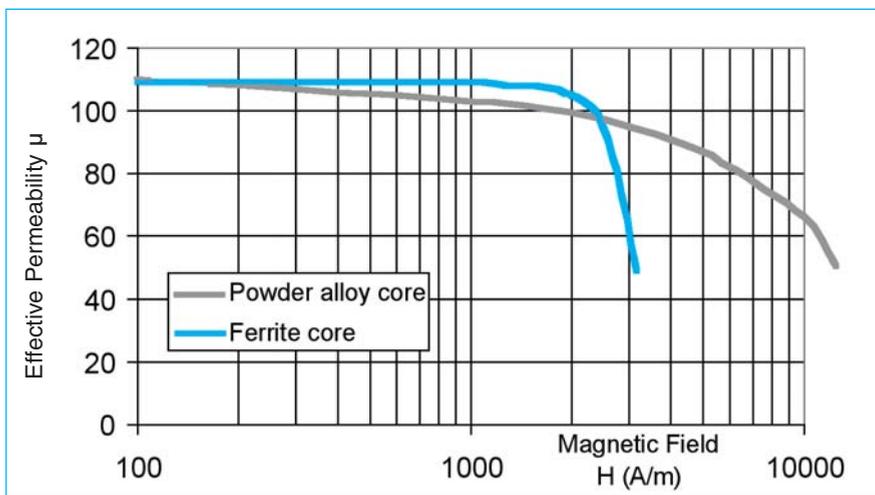


Figure 4: Saturation curve: ferrites have lower saturation, but flat response, while powder cores show high saturation with a continuous slope.

Ferrite cores are the third option. They have the lowest losses at high frequencies, and though the saturation is lower than in powder cores, the curve is completely flat. This curve allows the designer to optimize the core volume and gap size to the required energy to store. The result is very low distortion with a low turns count (10 to 25) and, finally, at the most affordable cost.

A practical Class D audio amplifier has been evaluated to measure the influence of the magnetic core on the distortion of the audio signal. The amplifier is driven by an International Rectifier IR2011S device, delivering up to 500 + 500 watts peak.

The reference design

The reference design is the IRAUDAMPI from International Rectifier. Complete details of the amplifier can be found at International Rectifier website, in this application we will focus on the output low pass filter design.

The switching frequency is 400 kHz; this frequency will be modulated by the low frequency audio signal through the PWM (Pulse Width Modulator). The MOSFET's (International Rectifier IRFB23N15D) are driven by the IR2011S high speed gate driver.



Figure 5: International Rectifier IRAUDAMPI demo board. Features 500W + 500W peak stereo power, efficiency 93% at 1 kHz and 100 watts. Voltage supply ± 50 Volts (allowed ± 25 to ± 60). Compact size: 100 x 140 x 38 mm.

In the original design, the output filter of each channel is made with an AVX capacitor (BF074E0474J) with 0.47 μ F) and a Micrometals inductor core (NPT0104, core T106-2). It has an inductance value of 18 μ H and it is wound with 37 turns of AWG18 magnet wire. This filter cut off frequency is 50 kHz (see annex 2 for details).

In one of the channels, the original inductor has been replaced by a FERROXCUBE TN26/11-3C20-A113. It has also an inductance of 18 μ H, but it is only wound with 13 turns of the same AWG18 wire.

Distortion and noise versus frequency and power are the key parameters to define the quality of an audio amplifier. The following curves compare the performance of the amplifier on each channel, taking into account that the

only difference between them is the magnetic material of the inductor and the winding count.

The measuring equipment used to test the amplifier performance is Audio Precision System Two. This equipment allows easy and fast measurements under several conditions. It is widely used in the audio industry. Each channel has been loaded with a 5 Ohms resistive load.

This first graph shows the total harmonic distortion and noise power percentage versus the output power of the amplifier. The percentage increases with the output power due to longer swing over the saturation curves (see figure 4). Here we can see that the performance of the ferrite is similar and slightly better under high power conditions.

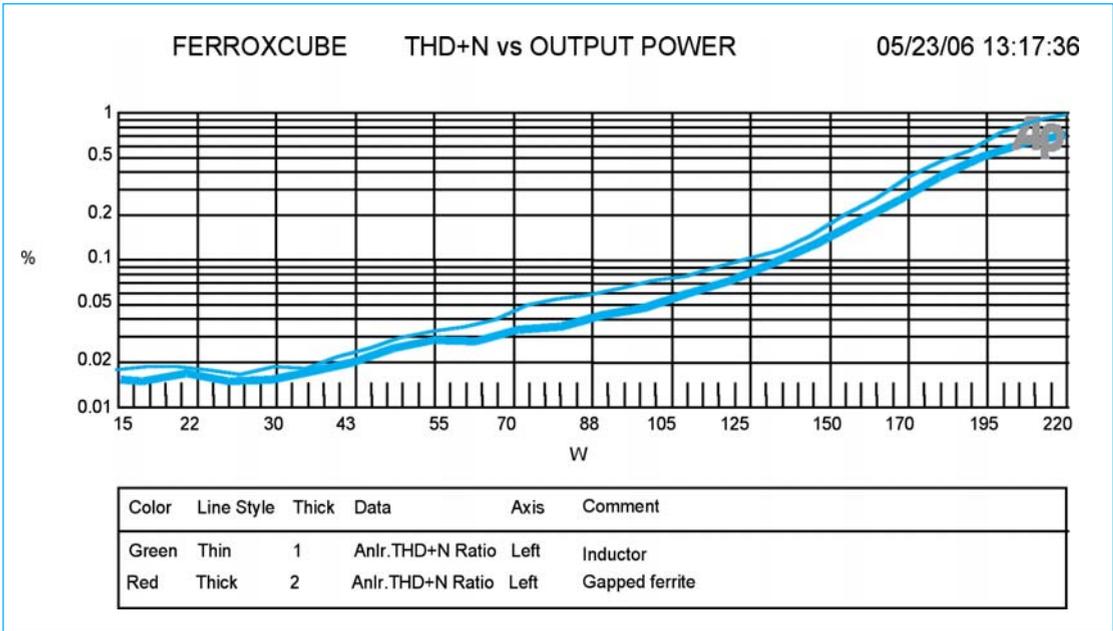


Figure 6: Distortion over output power percentage versus output power comparing powder alloy and ferrite core inductors. Amplifier input 10 kHz, load: 5 Ohms, voltage supply ± 50 Volts.

This second graph shows the same parameter (total harmonic distortion and noise percentage) over a frequen-

cy sweep over the audio spectrum at a fixed output power (in this case 100 watts). Again, the same result shows a

slightly better performance of the ferrite core over the powder core.

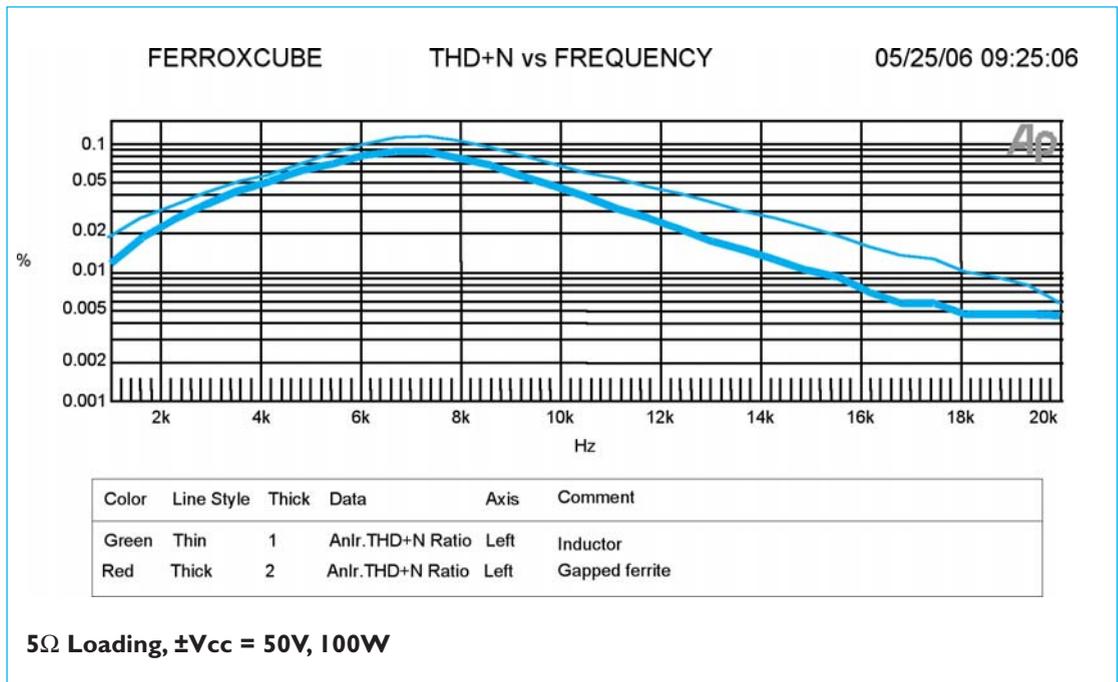


Figure 7: Distortion over output power percentage versus frequency comparing powder alloy and ferrite core inductors. Output power 100 watts, load 5 Ohms, voltage supply ± 50 Volts

Ferrite core design with Ferroxcube gapped toroids

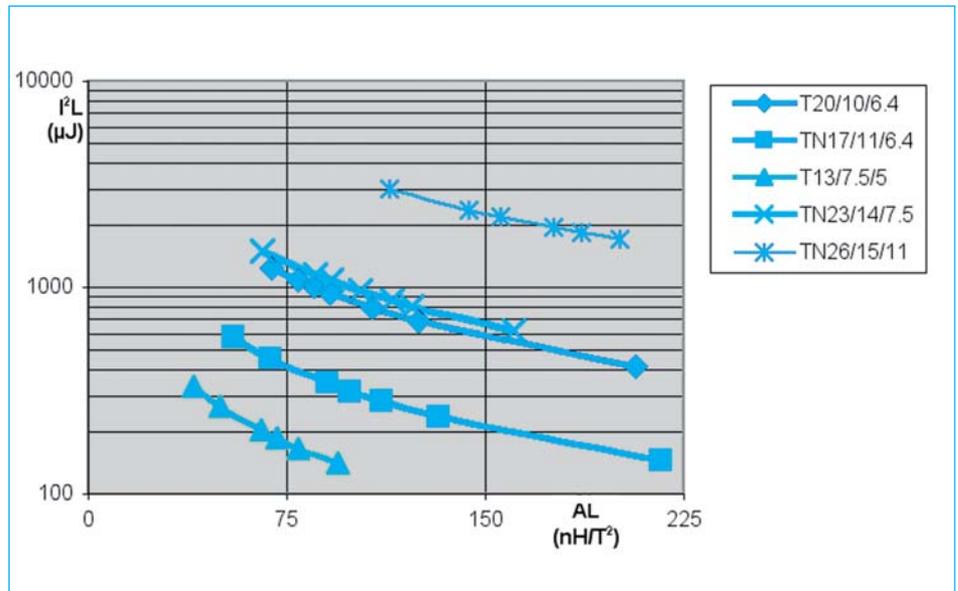
Ferroxcube offers a wide range of standard gapped toroids fitting in this application. The procedure shown below is intended to help the design engineer to choose the optimal (and therefore the most cost effective) product size and gap. It is important to note that custom cores and gap sizes are available upon request.

The procedure starts with 2 basic parameters: the inductance of the output filter (see annex to calculate the value out of the cut off frequency and load impedance) and the maximum current that will flow through the inductor (derived from the maximum power of the amplifier).

These parameters will be used to calculate the energy stored in the inductor:

$E = L \times I^2$, where L is the inductance in μH , I is the maximum current in Amperes, and E is energy in μJ

The next parameter to be taken into account is the size of the core in combination with the amount of energy to be stored in the inductor. In most of the cases the size of the core is limited by the board layout and mechanical constraints, so the designer has to



optimize the core to work in the saturation limit. The following graphs help to choose the right core able to stand the power. For each core size it is plotted the amount of energy capable to be stored and the maximum AL factor of the core. In annex I plots for every standard size can be found. Note that it is possible to make custom sizes and custom AL factors upon request.

After the selection of the core size and AL factor, the next step is to calculate the winding. The number of turns is derived from the next relation:

$$N = \sqrt{\frac{L \times 1000}{A_L}}$$

where L is the inductance in μH and AL is in nH/T^2 , and N is the number of turns.

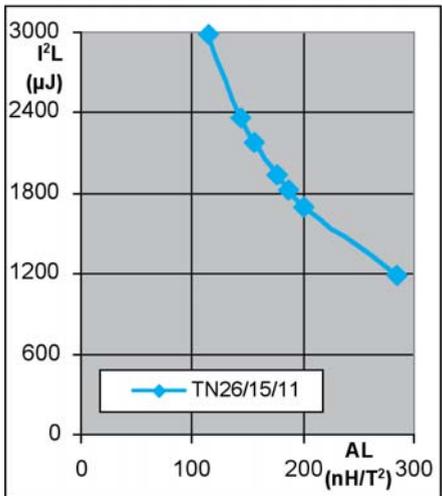
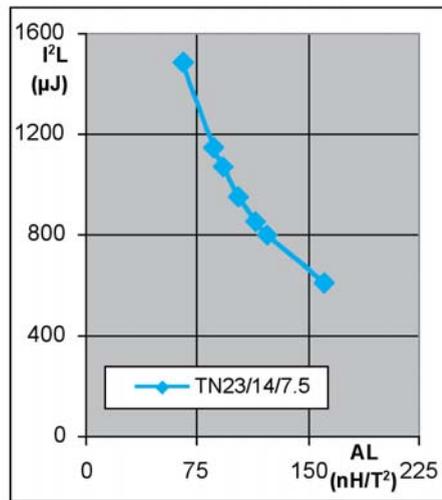
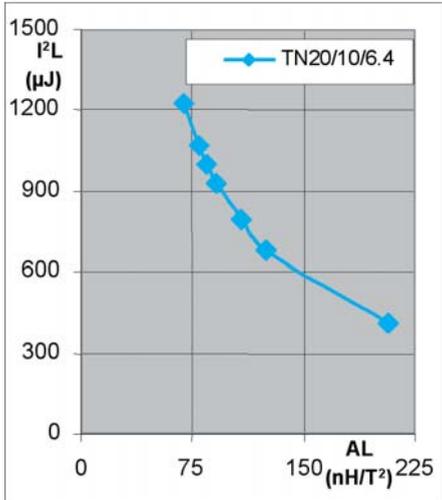
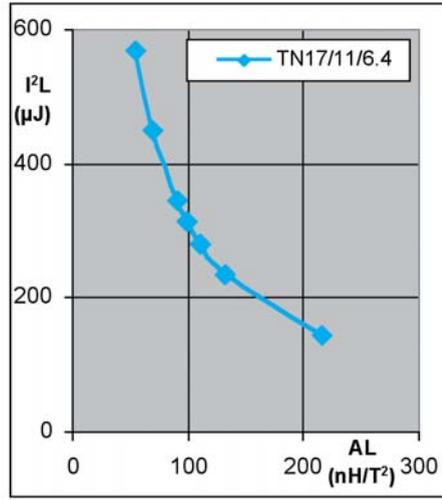
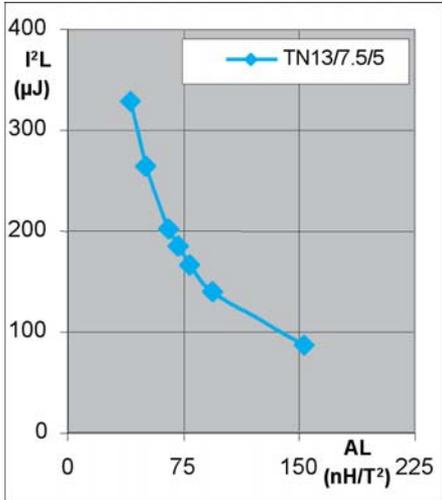
The wire gauge is fixed by the maximum DC resistance allowed for the inductor as well as by the current density that the wire can handle. DC resistance can be estimated with the following formula:

$R = (1 + OD - ID + 2 \times H) \times R_L \times N$, where R is the DC resistance of the inductor in mOhm, OD, ID and H are the outer, inner diameter and height of the core in mm, R_L is the resistance per meter of the selected wire gauge and N is the number of turns.

Annex 1: I²L curves for Ferroxcube gapped toroids

The following graphs show the energy storage capability of standard Ferroxcube gapped toroids. There are more sizes and AL values available and custom products can be made upon request.

Product dimensions are described as TN (toroid coated with Nylon) 13 (outer diameter) /7.5 (inner diameter) /5 (height).



Annex 2: Filter design basics

The most common and recommendable output filter is a simple second order Butterworth filter. They count a minimum number of components and show optimal flatness response while keeping a sharp cut off frequency.

The transfer function for a second order Butterworth filter has to follow this equation:

$$H(s) = \frac{1}{s^2 + \sqrt{2}s + 1}$$

The cut off frequency for this filter is located at $\omega_0 = 1$ rad/sec, so we should scale it by $\omega_c = 2\pi f_c$, being f_c the desired cut off frequency:

$$H(s) = \frac{\omega_c^2}{s^2 + \sqrt{2}\omega_c s + \omega_c^2}$$

The basic construction for such a filter is:

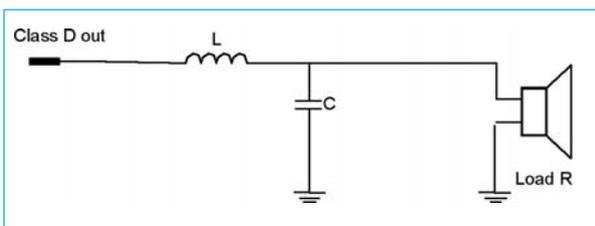


Figure 8: Second order low pass filter.

Calculating the transfer function of the circuit in the Laplace domain:

$$H(s) = \frac{1}{LC} \frac{1}{s^2 + \frac{1}{RC}s + \frac{1}{LC}}$$

Now calculating the L and C values:

$$\omega_c^2 = \frac{1}{LC} \quad \sqrt{2}\omega_c = \frac{1}{RC}$$

$$C = \frac{1}{2\sqrt{2}\pi f_c R} \quad L = \frac{\sqrt{2}R}{2\pi f_c}$$

These equations show that the inductor and capacitor values depend on the loudspeaker impedance. Therefore it is recommendable to have a switch to choose between 4 or 8 Ohms. This means that the inductor should have 2 windings in series, so the switch will select the first winding for the low inductance (and low impedance loudspeaker) or both windings for the high inductance filter.

Depending on the polarity of the amplifier voltage supply (bipolar $\pm V_{cc}$ or simple $+V_{cc}$) the output filter should be implemented accordingly, as shown in the following scheme:

Figure 10: Double inductor filter for simple supply.

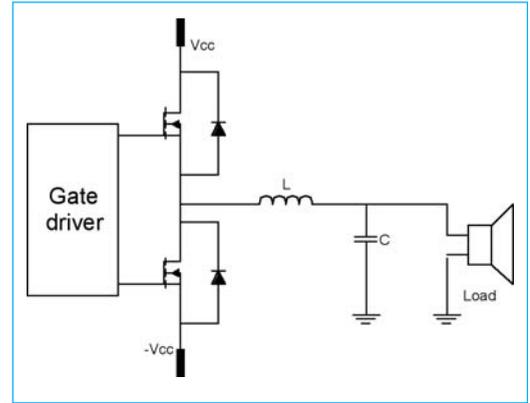


Figure 9: Simple filter with bipolar supply.

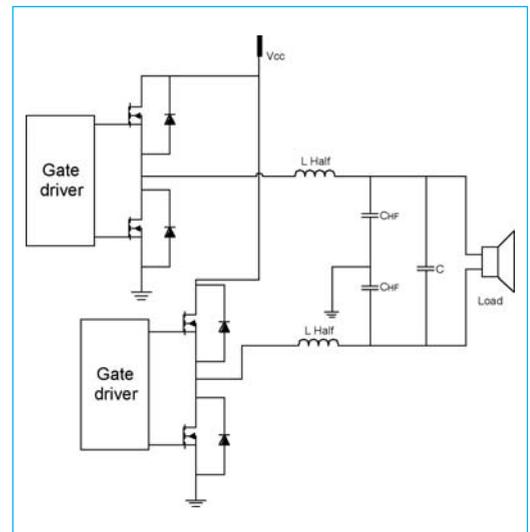


Figure 10: Double inductor filter for simple supply.

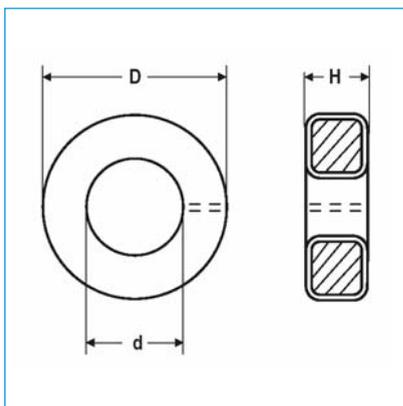
These equations and figures derive a table with capacitance and inductance values for several cut off frequencies and loudspeaker impedance values.

f_c (kHz)	R (Ohm)	L (μ H)	L Half (μ H)	C (μ F)
20	4	45	23	1.41
25	4	36	18	1.13
30	4	30	15	0.94
50	4	18	9	0.56
20	8	90	45	0.70
25	8	72	36	0.56
30	8	60	30	0.47
50	8	36	18	0.28

Product range and specifications

The cores are coated with Polyamide II (PAII), flame retardant in accordance with UL94V-2, UL file number E45228 (M). The inner and outer diameters apply to the coated toroid.

Contacts are applied on the edge of the toroid for isolation voltage test, which is also the critical point for the winding operation.



Core type	Dimensions (mm)			Effective parameters				Other	
	Outer diameter D (mm)	Inner diameter d (mm)	Height H (mm)	Core factor (mm ⁻¹)	Effective volume (mm ³)	Effective length (mm)	Effective area (mm ²)	Mass (g)	Isolation voltage (V)
TN13/7.5/5	13	6.6	5.4	2.46	368	30.1	12.2	1.8	1500
TN17/11/6.4	17.5	9.9	6.85	2.24	787	42.0	42	3.7	1500
TN20/10/6.4	20.6	9.2	6.85	1.43	1330	43.6	43.6	6.9	2000
TN23/14/7.5	24	13	8.1	1.69	1845	55.8	55.8	9.0	2000
TN26/15/11	26.8	13.5	11.6	0.982	3700	60.1	60.1	19	2000

Core type	AL (nH/T ²)	μ_{eff}
TN13/5-3C20-A40	40 ± 15%	90
TN13/5-3C20-A56	56 ± 15%	125
TN13/5-3C20-A67	67 ± 15%	147
TN13/5-3C20-A72	72 ± 15%	160
TN13/5-3C20-A79	79 ± 15%	173

Core type	AL (nH/T ²)	μ_{eff}
TN20/6.4-3C20-A68	68 ± 15%	125
TN20/6.4-3C20-A81	81 ± 15%	147
TN20/6.4-3C20-A87	87 ± 15%	160
TN20/6.4-3C20-A96	96 ± 15%	173
TN20/6.4-3C20-A109	109 ± 15%	200

Core type	AL (nH/T ²)	μ_{eff}
TN17/6.4-3C20-A52	52 ± 15%	90
TN17/6.4-3C20-A72	72 ± 15%	125
TN17/6.4-3C20-A88	88 ± 15%	147
TN17/6.4-3C20-A92	92 ± 15%	160
TN17/6.4-3C20-A104	104 ± 15%	173

Core type	AL (nH/T ²)	μ_{eff}
TN23/7.5-3C20-A65	65 ± 15%	90
TN23/7.5-3C20-A90	90 ± 15%	125
TN23/7.5-3C20-A106	106 ± 15%	147
TN23/7.5-3C20-A115	115 ± 15%	160
TN23/7.5-3C20-A124	124 ± 15%	173

Core type	AL (nH/T ²)	μ_{eff}
TN26/11-3C20-A113	113 ± 15%	90
TN26/11-3C20-A157	157 ± 15%	125
TN26/11-3C20-A185	185 ± 15%	147
TN26/11-3C20-A201	201 ± 15%	160
TN26/11-3C20-A217	217 ± 15%	173