

# A Comparison of Modular State-of-the-Art Switch Mode and Linear Audio Power Amplifiers

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## ABSTRACT

Modern commercially available, compact, low power audio power amplifiers are mostly designed around one of three main technologies. These are integrated circuit class AB, thick film hybrid class AB, and switch mode power amplifier modules. The decision to use a particular technology is not only based on idealised performance specifications, but also on the performance under realistic operating conditions, and cost-to-performance considerations. In this study, the performance of each amplifier technology is studied in ideal and realistic operating conditions with two amplifier designs for each technology category. Regulated and unregulated power supplies are used, in combination with ideal resistive and real-life complex impedance loudspeaker loads. For a fixed nominal supply voltage, the value of the different technologies with regard to noise, distortion and continuous output power is discussed. This results in an analysis of the cost effectiveness, or value, of currently competing technologies for high quality, low power, compact audio power amplifiers.

## 0. INTRODUCTION

Modular power amplifiers are almost universally chosen for low power, compact, audio power amplifiers because of cost-effectiveness and advantageous size-to-performance ratio.

The ever-growing list of modular power amplifiers makes selection very difficult. Datasheets for available power amplifier modules show the performance of the modules in various conditions, but do not reveal the performance-to-cost ratio, or value. This paper stems from the need to justify the choice to use a particular contemporary power amplifier module, of a particular technology, when budget restrictions are in place.

## 1. POWER AMPLIFIER CONFIGURATIONS

There are several classes of power amplifier configurations. The configurations most commonly used in audio power amplifiers are class AB and switch mode configurations.

### 1.1. Class AB Audio Power Amplifiers

Class AB power amplifiers have been used for decades in audio reproduction, and have become well accepted. They are relatively easy to design for mass production, and can be configured to give almost any required output power. The total harmonic distortion and noise (THD+N) can be reduced to 0.001% or less below 10kHz at reasonable output levels [1, p. 290]. This remaining THD+N is mostly noise and crossover distortion.

It is possible to buy class AB power amplifiers as nearly complete modules. These fall into two main categories: integrated circuit (IC) and thick film hybrid (TFH). The IC is a circuit made on one piece of silicon, normally encased in plastic, with metal legs. The TFH is constructed from small discrete components mounted on an aluminium substrate, which is then fitted with a plastic cover and metal legs.

ICs are generally smaller and cheaper, with less output capability and lower maximum operating voltages. They also tend to have more comprehensive internal protection functions.

The main disadvantage of the class AB power amplifier is low efficiency, caused by losses in the output devices operated in their linear regions. Depending on the bias current, the maximum efficiency for a sine wave signal is theoretically just under 78.5% [2, 3], but practically about 70% [3, p. 52]. With real music signals, the efficiency is in the range of 30-50%, which makes it necessary to dissipate significant amounts of heat from the amplifier. Class AB ICs and TFHs are widely available, cost-effective, and used widely in compact audio power amplifier products.

### 1.2. Switch Mode Audio Power Amplifiers

Switch mode amplifiers produce the output signal by pulse width modulating and amplifying the input signal. This is demodulated later by filtering out high frequency switching components either in the loudspeaker driver itself or in a filter at the amplifier output to recover the amplified signal.

Switch mode amplifier designs have existed since the 1960s, but only relatively recently has the distortion performance been improved sufficiently to use them for audio purposes [3].

Because the output devices are nominally either in cut-off or saturation, the switch mode amplifier is very efficient. Its efficiency is typically 80-90% for a sine wave signal. This is its greatest advantage, significantly reducing the heat generated in the amplifier.

One current disadvantage of the switch mode amplifier is complexity of design, increased by the need to conform to stringent EMC standards.

At the present time, complete switch mode amplifier modules are available from several manufacturers. An increasing number of IC manufacturers are also offering FET driver ICs and information about how to incorporate them into switch mode amplifiers.

## 2. PERFORMANCE MEASUREMENTS

### 2.1. Idealised Versus Realistic Conditions

The specifications for a component or a whole system are often given based on measurements taken in idealised conditions. This provides a quick rough comparison for a broad range of operating conditions. However, when a component is taken into use in a real system, the operating conditions may differ significantly from ideal. In the case of a power amplifier, the main conditions that vary are the power supply and the load.

An ideal power supply for a power amplifier is regulated DC. This kind of supply can easily be made for low current circuits such as preamplifiers, but power amplifiers use very high current peaks. High current regulated supplies can be constructed using switch mode or linear technology, but are very rarely seen in low power audio power amplifiers.

Commonly, the power supply is based on a transformer, full wave rectification, and large reservoir capacitors for smoothing and supplying current peaks. There is a voltage drop across the resistance of the transformer windings. At high output power, this manifests itself as a significant supply voltage reduction, lowering the voltage headroom and hence usable output power of the power amplifier. The size of the reservoir capacitors affects the available peak current, and hence the peak power of the amplifier. Poor smoothing can degrade the noise performance of a power amplifier. Power amplifiers are mostly specified into 4Ω or 8Ω resistive loads. These present a relatively easy load for the power amplifier. In practice, audio power amplifiers are nearly always used with moving coil loudspeakers. The drivers, typically mounted in vented cabinets, present a complex load to the power amplifier with significant reactive loading. The impedance minima are below the nominal impedance of the driver, and the peaks around these are typically many times the magnitude of the minimum impedance. The phase of the load varies typically within the range of  $\pm 60^\circ$ . The result of these factors is that the amplifier has to dissipate more power than with a resistive load. Some amplifiers become

unstable when used with highly reactive loads, or their performance can be otherwise degraded.

### 2.2. Frequency Response

The frequency response of the amplifier is not critical for this work, since the frequency response of the currently available modules is more than sufficient for audio applications. In high quality systems, the frequency response is limited prior to the power amplifier by active filters, and tailored by tone controls. In a complete reproduction system, deviation from flatness of response is typically dominated by the loudspeaker. In this paper, frequency response is simply checked for flatness in the typical range of 40Hz to 22kHz.

### 2.3. Noise

Noise generated by the amplifier is a very important consideration because it may limit the available dynamic range of an audio power amplifier and may annoy the user. Idle channel noise is also regarded by some users as a measure of system quality. Output noise voltage and equivalent input noise (EIN) are measured in this study.

### 2.4. Distortion

As yet there is no widely recognised single measurement of distortion that translates directly into perceived quality. The main techniques of distortion measurement are harmonic distortion (THD and THD+N) and various intermodulation distortion measurements (SMPTE, CCIF, DIM/TIM) [4,5,6].

THD+N, the most widely used measurement, comes closest to providing a single figure of merit to say that there are no major problems in the device under test, particularly when measured at several frequencies [7, p. 32, 8]. The subjective quality of a system may be more dependent on its intermodulation distortion than its harmonic distortion [9].

In this study the goal is comparative measurement of quality and value of the different modules. THD+N values at various frequencies using different loads and power supplies are measured for this purpose.

### 2.5. Output Power

In this paper, continuous output power is measured at levels of 0.1% and 1% THD+N.

### 2.6. Efficiency

Efficiency is important in high power amplifiers with limited space for heatsinks and cooling. In compact, low power, audio power amplifiers, the mean power levels are typically low, and so the heat generated in the amplifier can be dissipated relatively easily. For this reason, efficiency is not directly measured in this paper.

## 3. DESCRIPTION OF AMPLIFIERS

There are many ways of choosing a set of amplifiers to test. By choosing based on price, the benefits of an amplifier only slightly out of the price range may go unnoticed. Choosing based on performance specifications may also be misguided because the amplifier may have been specified under ideal conditions, or under different conditions to other amplifiers.

Power supply voltage level has great impact on reservoir capacitor choice, efficiency, method of generating another set of voltages for low voltage signal conditioning, etc. Most low power audio power amplifiers use a voltage supply of  $\pm 25V$  to  $\pm 35V$ .

Amplifiers recommended for use with an output swing of about  $\pm 35V$  were chosen. This means a supply of  $\pm 35V$  for single ended designs, or +35V and 0V for bridged designs. The chosen amplifiers are commonly available, popular, and sold for use in high quality systems. The amplifier descriptions can be seen in table 1.

Table 1. Comparison of amplifier features

Amp	Technology	Package	Output stage	Protection	Other supplies
1	Class AB	IC	Single-ended BJT	Yes	No
2	Class AB	IC	Single-ended, DMOS	Yes	No
3	Class AB	TFH	Single-ended quasi-compl. BJT	No	No
4	Class AB	TFH	Single-ended, compl. emitter-follower BJT	No	+12V
5	Switch mode	Demo board	Single-ended N-ch. MOSFET	No	No
6	Switch mode	Complete module	H-Bridged N-ch. MOSFET	No	±12V

The six amplifiers represent five different manufacturers. Amplifiers 1 to 4 were assembled with the extra components required to make the circuit recommended in their datasheet, but with equal input impedance. Components were placed on double-sided PCBs with good ground planes on both sides. The PCBs were specially designed for this work.

The gains of the amplifiers are different because of the manufacturers' recommendations. This has been accounted for in calculating the equivalent input noise.

The heatsinks used are rectangles of 5mm thick aluminium sheet. They are sufficient to keep the heatsink temperature rise to 40° or less when an amplifier is playing music material.

#### 4. DESCRIPTION OF POWER SUPPLIES

Mains voltage for the power supplies comes from a 3.5kVA variac. For the unregulated power supply three toroidal mains transformers are used. These have dual 0-25V secondary windings with ratings 60VA, 120VA and 250VA. The AC voltage is full wave rectified by a diode bridge and smoothed by 4700µF reservoir capacitors. This value was chosen because it is in common use. The value is not very critical as the power output is measured for continuous output power. The regulated power supply is based on LM317/337 voltage regulators with pass transistors and over-current protection. Extra ±12V supplies needed by some amplifiers were provided by a regulated laboratory power supply. Since power amplifiers typically use little current from these supplies, it is fair to assume that the low voltage supplies already in the audio system can be used also for the power amplifier with no extra cost or reduction in quality.

#### 5. COST OF AMPLIFIER AND POWER SUPPLY

The costs of all parts are based on general mass production market prices. The cost of the regulated power supply was not calculated because it is not considered competitive for a low power audio power amplifier. The costs (see fig. 1) were normalised to the cost of the complete power amplifier solution based on amplifier 1 using a 60VA unregulated power supply.

There is no standard for incorporating the cost of an audio product into its perceived quality to obtain its performance to cost ratio, or value. In this case the normalised cost either multiplies performance data for which a low figure represents high quality, or divides performance data for which a high figure represents high quality.

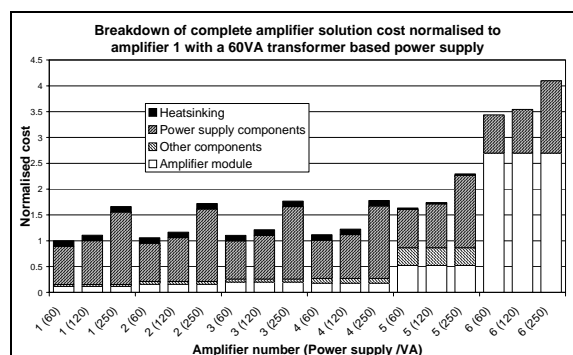


Fig. 1. Breakdown of amplifier costs, normalised to amplifier 1, assuming a 60VA unregulated power supply.

## 6. MEASUREMENTS

Before any measurements were made, the power supplies and amplifiers were tested to ensure that they function as expected without oscillation, unusually high noise, or distortion. All measurements were made using the same measurement system<sup>†</sup>.

### 6.1. Frequency response and Noise

The 60VA unregulated power supply was used in these measurements. With the amplifier connected to an 8Ω resistive load the frequency response was measured to be sure that it is flat ( $\pm 0.2$ dB) from 40Hz to 22kHz. The gain was recorded and can be seen in table 2.

To measure noise, the amplifier input was grounded. The load was disconnected because it is a very open construction that, especially with connected wires, acts as an antenna, picking up 50Hz magnetic noise from the lab space. The bandwidth of the measurement system was set to 21kHz, using an AES17 20kHz brickwall filter. The A-weighted noise voltage at the amplifier output was measured. The results can be seen in table 2.

Table 2. Cost, noise and gain. EIN – equivalent input noise. All noise voltages are A-weighted.

Amplifier	1	2	3	4	5	6
Technology	AB IC	AB IC	AB TFH	AB TFH	sw. mode	sw. mode
Normalised Cost	1.00	1.06	1.10	1.12	1.63	3.44
Noise voltage (µV)	55	32	25	21	165	76
Gain (dB)	24.0	30.4	33.6	30.0	25.3	27.0
EIN (µV)	3.47	0.97	0.52	0.66	8.96	3.39
EIN x normalised cost	3.47	1.02	0.58	0.74	14.64	11.67

### 6.2. Determining the loudspeaker load

The impedance of a typical nominal 4Ω loudspeaker bass driver in a vented cabinet was measured from 10Hz to 1kHz. The tuning frequency of the cabinet was found to be 35Hz. The first phase maximum above this is +30.3° at 58Hz, where the impedance magnitude is 5.86Ω. All tests using a real loudspeaker as a load used this driver in this cabinet.

Due to the spectral content of music, more power is needed at low frequencies. Because of driver and cabinet resonances, it is at low frequencies that the loudspeaker load is most different to the resistive load. For these reasons, the output power and distortion tests with the loudspeaker load were carried out only at 58Hz.

<sup>†</sup> Audio Precision System Two Cascade Plus

### 6.3. Continuous output power

The input to the amplifier, a fixed frequency sinewave, was ramped up slowly and the power output and THD+N were recorded in a 21kHz bandwidth set by an AES17 20kHz brickwall filter. At 58Hz, each amplifier was tested with 4 $\Omega$  resistive, 8 $\Omega$  resistive, and loudspeaker loads. In the case of the loudspeaker load, the measured power is based on the amplifier output voltage and the real part of the loudspeaker impedance (5.06 $\Omega$ ) to measure the power dissipated in the driver. Other test frequencies were chosen to cover the rest of the audio band. 1kHz was chosen because it is a standard frequency for testing, 7kHz was chosen as the highest frequency that has the third harmonic in a 21kHz bandwidth. 14 kHz was chosen because it represents the high end of the audio bandwidth and its third harmonic is within 42kHz, another standard AES17 filter bandwidth. The assumption made here was that the harmonics would decrease in amplitude as their order increases and the THD+N level as measured from these is representative of the true unlimited bandwidth values.

At 1kHz, 7kHz and 14kHz, the loads used were 4 $\Omega$  resistive and 8 $\Omega$  resistive. In the 14kHz case, the measurement system bandwidth was increased to 42kHz by using an AES17 40kHz brickwall filter

The output power for 0.1% and 1% THD+N was recorded to the nearest 0.5W. The comparisons of results can be seen in appendix A where Figs. 1-9 show continuous power outputs of the amplifiers with different power supplies, at different frequencies and with different loads.

Figs. 10-18 in appendix A show the value of the amplifier, heatsink and power supply combination in terms of the output power. This could be considered the measure of "bang for the buck", or a measure of value for money. They are shown as  $10\log(\text{power}/\text{total cost})$  for simple viewing. The total cost has been normalised to the cost of amplifier 1 with a 60VA unregulated power supply.

### 6.4. Distortion at a known power

Using the data generated in section 6.3., it is possible to read the THD+N at any output power. The power chosen was the power when the output voltage swing is  $\pm 17.5V$ , half the theoretical lossless maximum. This corresponds to 19W into an 8 $\Omega$  resistive load, 38W into a 4 $\Omega$  resistive load, and 30W into the real part of the loudspeaker load at 58Hz. The results are seen in the appendix B, figs. 1-9.

To compare the value of the amplifiers in terms of their distortion, the THD+N was multiplied by the total cost of the amplifier, heatsink and power supply combination. The costs were normalised to the cost of amplifier 1 with the 60VA unregulated power supply. The results are shown in appendix B, figs. 10-18.

## 7. RESULTS AND DISCUSSION

### 7.1. Noise

This section discusses table 2. The lowest absolute output noise voltage and EIN are shown by the TFHs (amplifiers 3 and 4). The switch mode amplifiers (5 and 6) show the poorest noise performance. Amplifier 2, an IC, comes close to the EIN performance of the TFHs.

In most cases, higher output noise also means higher EIN, but in the case of amplifier 1, with quite low output noise the EIN is quite high because of its low gain. The noise performance of linear amplifier modules, particularly TFHs is currently better than that of switch mode amplifier modules.

### 7.2. Value In Terms Of Noise

This section discusses table 2. If EIN multiplied by normalised cost is an inverse measure of value, then the TFH power amplifier modules (3 and 4) have the highest value, followed by the ICs (1 and 2). The switch mode amplifiers (5 and 6) are considerably lower in value. In terms of noise performance, linear amplifiers

currently offer higher value than switch mode amplifiers. Among linear amplifiers, TFHs offer more value than ICs.

### 7.3. Continuous Output Power

This section discusses the main features of figs. 1-9 in appendix A. The continuous power output performance of the IC amplifiers (1 and 2) is often degraded by their protection circuitry, particularly at low frequencies with a 4 $\Omega$  resistive load. Some data could not be measured for amplifier 1 at high frequencies because it is unstable and the measurement sweep could not be completed. Data are also missing for amplifier 5 at high frequencies at 0.1% THD+N because the output at all power levels had greater than 0.1% THD+N. In terms of continuous power output, the amplifiers perform similarly with the 8 $\Omega$  resistive load at 1kHz and 7kHz.

These results are particularly interesting for two reasons. Firstly, linear amplifiers perform similarly while switch mode amplifiers show clearly different output power to each other. This suggests that switch mode technology is not as mature as linear technology because the optimum performance has not been found by all manufacturers. Secondly, the most common use of switch mode amplifiers is as bass amplifiers, but these results suggest that their efficiency advantage over linear amplifiers is greater at high frequencies.

With the loudspeaker load at low frequencies, the performance comparison resembles the performance comparison with the 8 $\Omega$  resistive load. When the supply voltage is kept constant, the maximum output power from any non-protecting amplifier increases with the VA rating of the transformer. The output of the TFH amplifiers appears to almost double from the 60VA unregulated power supply to the regulated supply. In many cases, the switch mode amplifiers show a higher output than the linear amplifiers when using the lower rated supplies. This is particularly the case at higher frequencies, with the 4 $\Omega$  resistive load, and at the 1% THD+N level. It is caused by the greater efficiency of the amplifier topology.

The IC amplifiers (1 and 2) do not always show a higher continuous power output when used with a larger power supply, and they do not perform as well as TFHs with low impedance loads. The TFH amplifiers (3 and 4) show the most consistent output capacity at different frequencies. One of the switch mode amplifiers has higher output at low frequencies, while the other has higher output at higher frequencies.

### 7.4. Value In Terms Of Continuous Output Power

This section discusses figs. 10-18 in appendix A. In this section, high value means high continuous output power to cost ratio.

With all loads, and at all frequencies, it can be seen that the linear amplifier solutions (1-4) offer the highest value, and show similar performance. Switch mode amplifier 5 offers less value, and amplifier 6 offers considerably less.

At low frequencies with the 4 $\Omega$  resistive load, amplifier 1 offers lower value for higher VA rated power supplies. This is because its internal protection circuitry reduces the available output power.

At low frequencies, the amplifiers offer similar value for both 0.1% and 1% THD+N levels. At higher frequencies, the value at the 0.1% THD+N level is very much lower for some amplifiers because of increased distortion levels. Switch mode amplifier 5 is the most affected by this phenomenon.

In the case of an amplifier functioning normally with no adverse protection circuitry effects, value with different transformers is similar. This suggests that a larger transformer is money well spent. When looking for the optimum transformer rating, in most cases, the 120VA transformer offers the highest value. This is a combination of the higher performance and low cost increase compared to the 60VA power supply. This suggests that for any given power supply voltage and load, there is an ideal transformer rating to give optimum value.

### 7.5. Distortion At A Known Power

This section discusses figs. 1-9 in appendix B. Some data are missing for IC amplifiers 1 and 2 because their poorly designed internal protection circuitry prevents them from reaching the required output power levels. At low frequencies, particularly with the 4Ω resistive load, it is very difficult to see trends in the results because the protection circuits in the ICs (amplifiers 1 and 2) and current limiting effects increase THD+N at some output powers.

When the amplifiers function normally with no protection or current limiting problems, the differences between measurements using different power supplies appear random. There should be no difference with power supplies of good quality because the power at which THD+N is measured is well below the point at which hard clipping occurs. It is not limited by the power supply voltage level, but by the non-linearity of the amplifier.

Amplifiers 3, 5 and 6 are the most consistent in their THD+N performance. This in itself is a benefit. With the loudspeaker load, differences in THD+N between the amplifiers are very small.

The performance of the amplifiers is most similar at lower frequencies and with the loudspeaker load. The linear amplifiers (1-4) show the lowest THD+N, although the performance of the ICs (1 and 2) is degraded by poorly designed internal protection circuitry. At high frequencies the spread between amplifiers is significantly greater. TFH amplifier 3 shows the most consistent THD+N performance across frequency.

### 7.6. Value In Terms Of Distortion

This section discusses figs. 10-18 in appendix B, in which high THD+N multiplied by normalised cost is thought of as low value. In many cases, the amplifier solution using the 60VA transformer appears to have the greatest value. This is because of its lower cost. Trends are hard to see again, for the same reasons outlined in the previous section.

At low frequencies with the 4Ω resistive load the value offered by the IC amplifiers (1 and 2) is often low because of the performance degradation caused by their poorly designed internal protection circuitry.

With the loudspeaker load, the values offered by the different amplifiers are more equal. Amplifiers 1-3 offer the most value, followed by 4, 6 and 5.

The spread of value offered by amplifiers is wide. Switch mode amplifiers offer less value than linear amplifiers because they show poorer performance and have a higher cost. The most consistent, high value across frequency and with different loads is shown by TFH amplifier 3.

### 8. SUMMARY

The aim of the work was to compare a set of currently commercially available power amplifier modules for use in high quality, low power, compact audio power amplifiers. The cost of mass-produced amplifier solutions using these amplifiers with various power supplies was calculated. The amplifiers were tested in ideal and realistic conditions. Equivalent input noise, output power and THD+N at a known power were measured for each amplifier while varying the power supply and load. Combining the normalised cost of the amplifiers with the measurement results, the relative value of the amplifier solutions was calculated.

The IC based amplifier solutions are the cheapest, closely followed by the TFH based solutions. For these types of amplifier solutions, the power supply accounts for most of the cost, and amplifier circuit cost is non-critical. The switch mode amplifier solution costs are more varied, but for a given power supply, more expensive because of the higher cost of the amplifier section.

The real loudspeaker load increases amplifier distortion compared to resistive loads, but a comparison of continuous power output between different amplifiers is similar to that of an 8Ω resistive load.

Using an unregulated power supply reduces the output of an amplifier compared to a regulated power supply. Switch mode amplifiers are least affected by this. In this work, it was found that there is an optimum size of transformer for given voltage and load conditions, regardless of amplifier choice.

The switch mode amplifiers showed greater variation in performance and cost than the linear amplifiers. This suggests that switch mode technology is not yet mature enough to produce consistent and competitive value for audio applications.

Of the six amplifiers tested, the most value overall is currently offered by TFH amplifiers. Switch mode amplifiers offer the least value, and there appears to be little justification at the present time for using them in high quality, low power, compact audio power amplifiers.

### 9. ACKNOWLEDGEMENTS

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APPENDICES

Appendix A. Continuous output power comparison charts

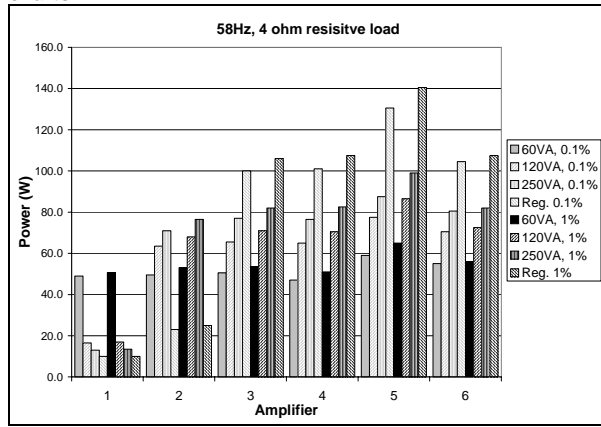


Fig. 1. Continuous output power of amplifiers at 58Hz into a 4Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

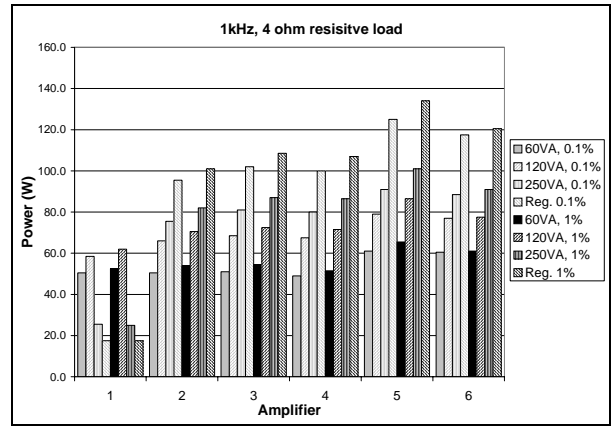


Fig. 4. Continuous output power of amplifiers at 1kHz into a 4Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

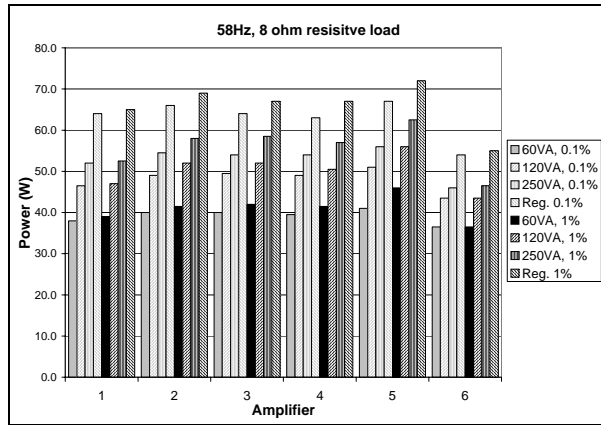


Fig. 2. Continuous output power of amplifiers at 58Hz into an 8Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

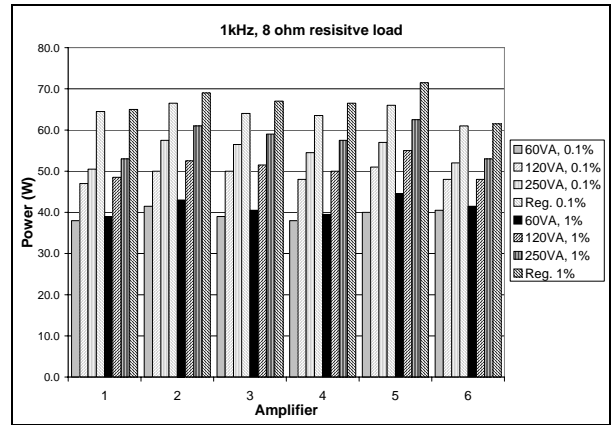


Fig. 5. Continuous output power of amplifiers at 1kHz into an 8Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

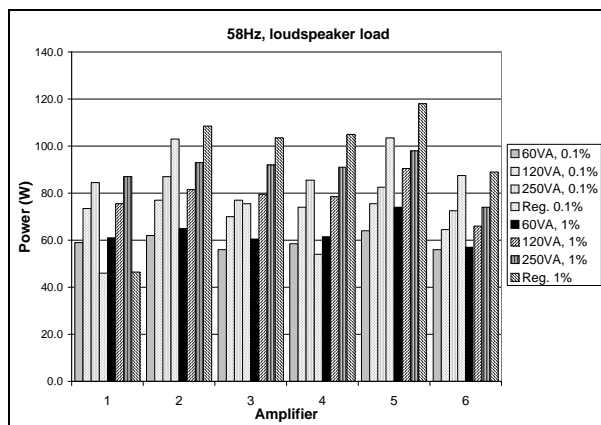


Fig. 3. Real part of continuous amplifier output power at 58Hz into the loudspeaker load. Measured with all power supplies at 0.1% and 1% THD+N

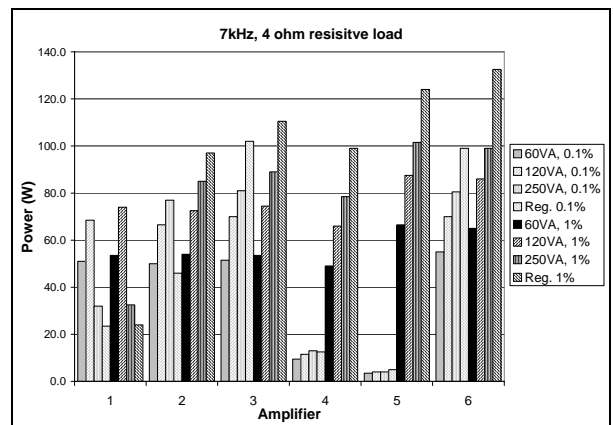


Fig. 6. Continuous output power of amplifiers at 7kHz into a 4Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

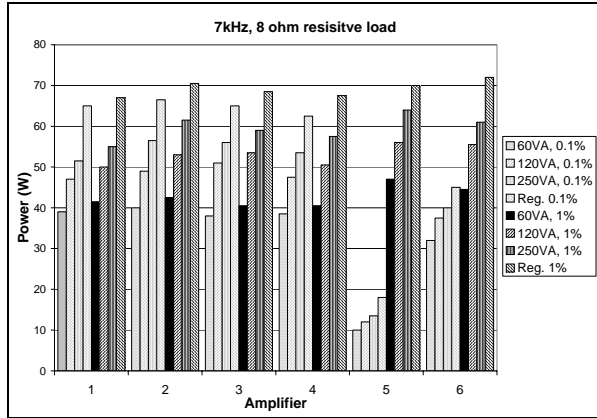


Fig. 7. Continuous output power of amplifiers at 7kHz into an 8Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

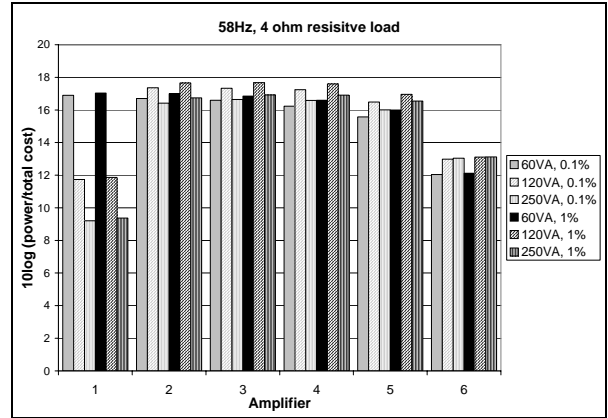


Fig. 10. Ratio of continuous output power and total cost at 58Hz into a 4Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

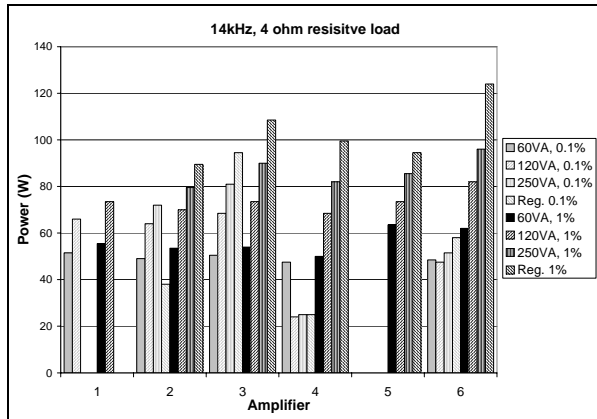


Fig. 8. Continuous output power of amplifiers at 14kHz into a 4Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

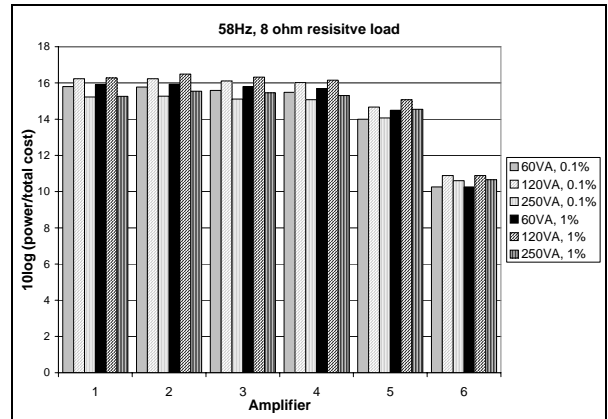


Fig. 11. Ratio of continuous output power and total cost at 58Hz into an 8Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

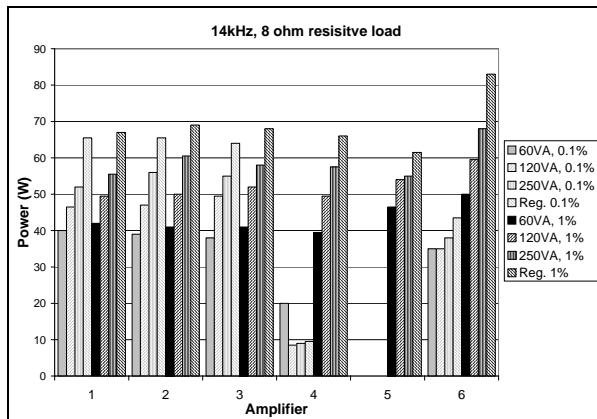


Fig. 9. Continuous output power of amplifiers at 14kHz into an 8Ω resistive load. Measured with all power supplies at 0.1% and 1% THD+N

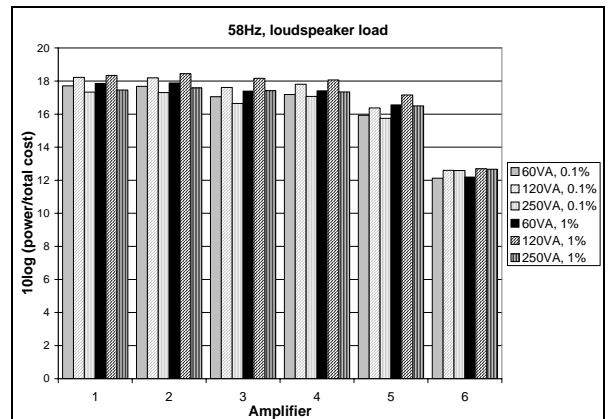


Fig. 12. Ratio of continuous output power and total cost at 58Hz into the loudspeaker load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

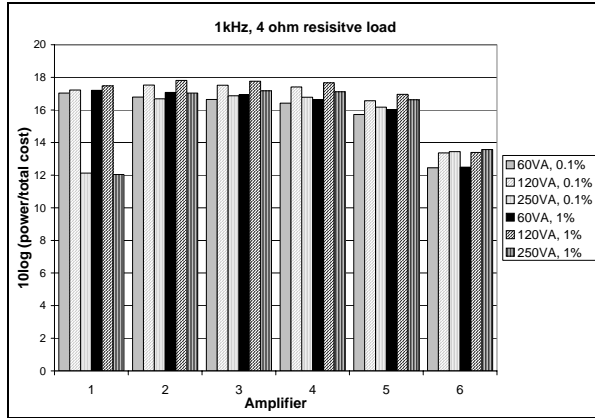


Fig. 13. Ratio of continuous output power and total cost at 1kHz into a 4Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

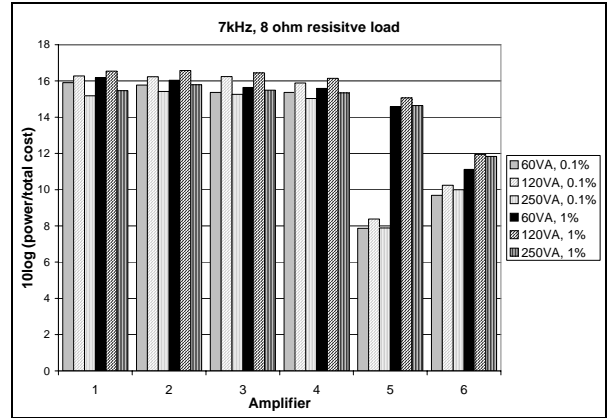


Fig. 16. Ratio of continuous output power and total cost at 7kHz into an 8Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

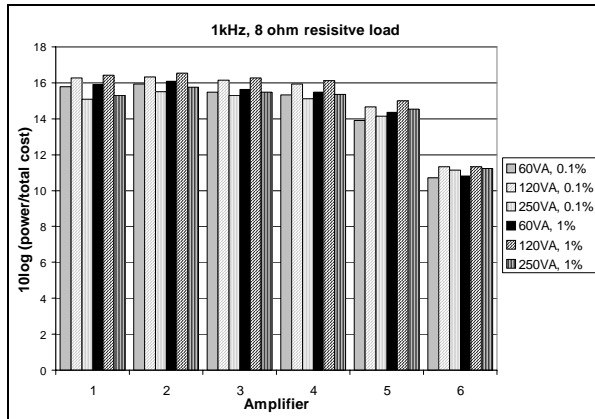


Fig. 14. Ratio of continuous output power and total cost at 1kHz into an 8Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

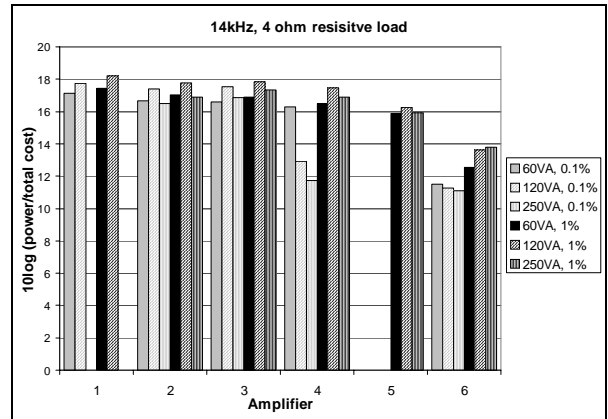


Fig. 17. Ratio of continuous output power and total cost at 14kHz into a 4Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

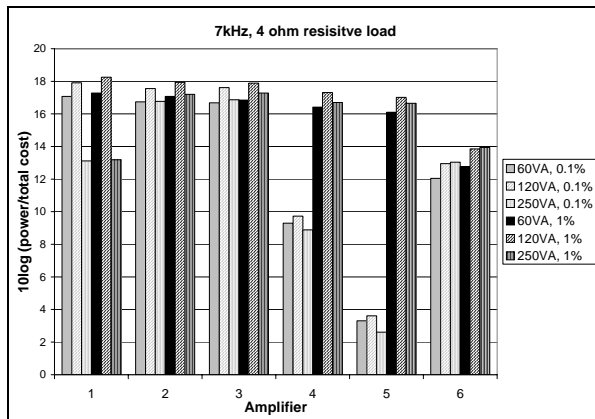


Fig. 15. Ratio of continuous output power and total cost at 7kHz into a 4Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N

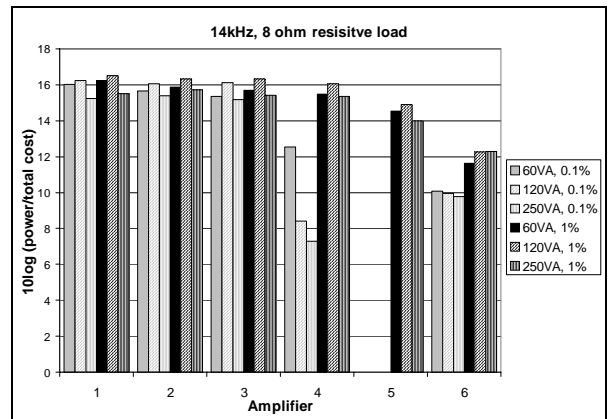


Fig. 18. Ratio of continuous output power and total cost at 14kHz into an 8Ω resistive load. Measured for all amplifiers and unregulated power supplies at 0.1% and 1% THD+N



**Appendix B. Comparison charts for THD+N at a known power**

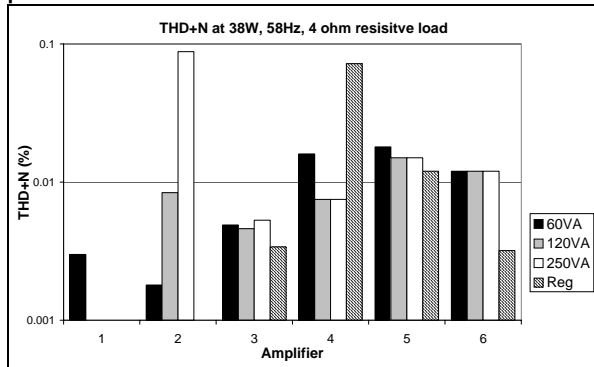


Fig. 1. THD+N of amplifiers at 58Hz outputting 38W into a 4Ω resistive load. Measured with all power supplies.

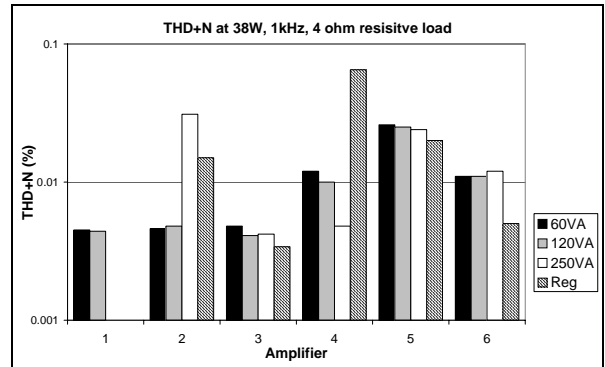


Fig. 4. THD+N of amplifiers at 1kHz outputting 38W into a 4Ω resistive load. Measured with all power supplies.

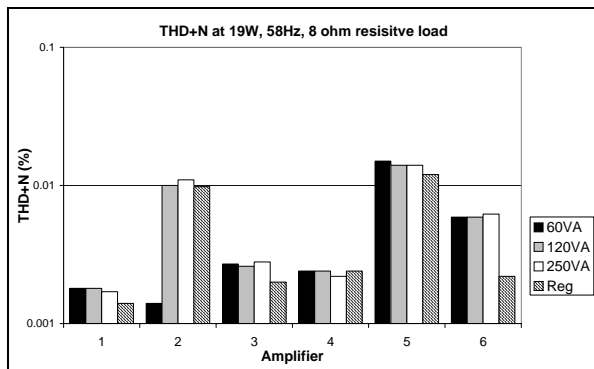


Fig. 2. THD+N of amplifiers at 58Hz outputting 19W into an 8Ω resistive load. Measured with all power supplies.

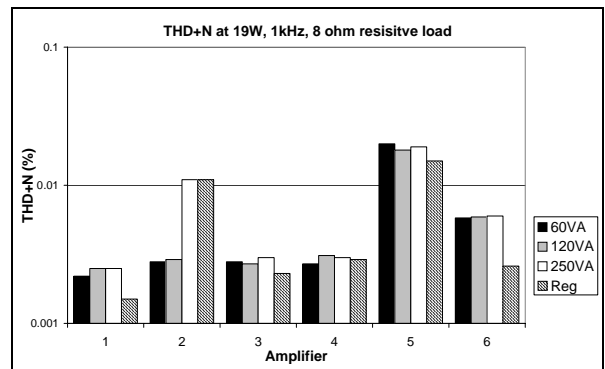


Fig. 5. THD+N of amplifiers at 1kHz outputting 19W into an 8Ω resistive load. Measured with all power supplies.

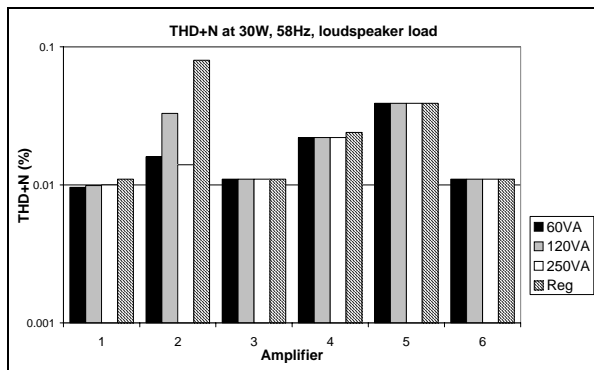


Fig. 3. THD+N of amplifiers at 58Hz outputting 30W into the loudspeaker load. Measured with all power supplies.

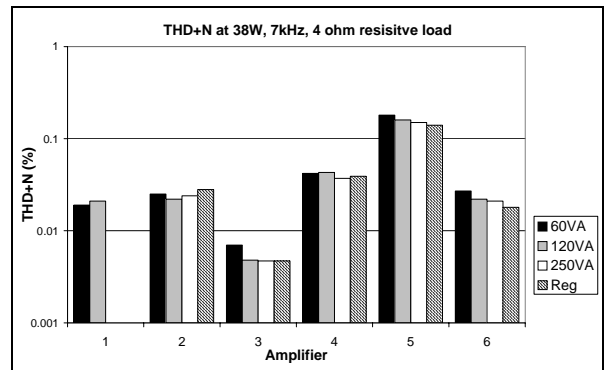


Fig. 6. THD+N of amplifiers at 7kHz outputting 38W into a 4Ω resistive load. Measured with all power supplies.

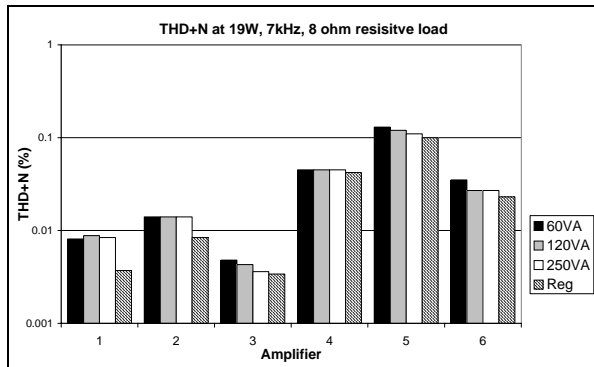


Fig. 7. THD+N of amplifiers at 7kHz outputting 19W into an 8Ω resistive load. Measured with all power supplies.

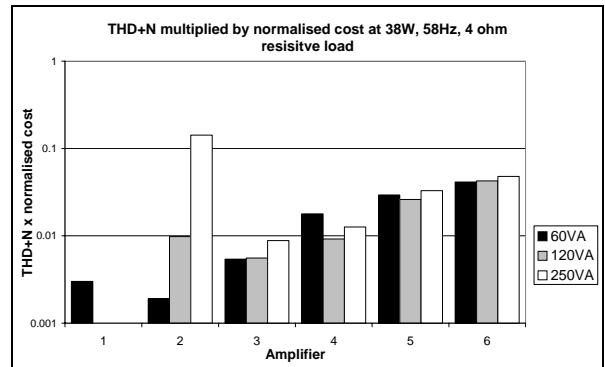


Fig. 10. THD+N multiplied by cost of amplifiers. Measured at 58Hz, outputting 38W into a 4Ω resistive load. Measured with unregulated power supplies.

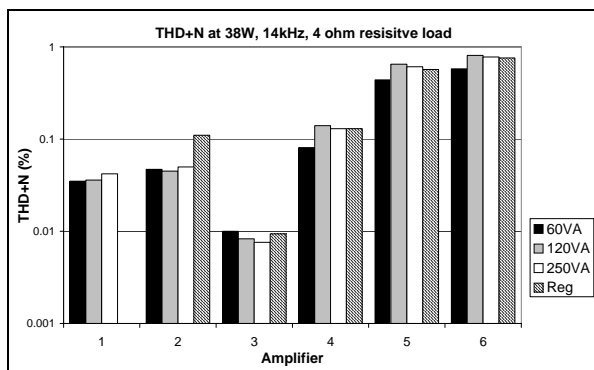


Fig. 8. THD+N of amplifiers at 14kHz outputting 38W into a 4Ω resistive load. Measured with all power supplies.

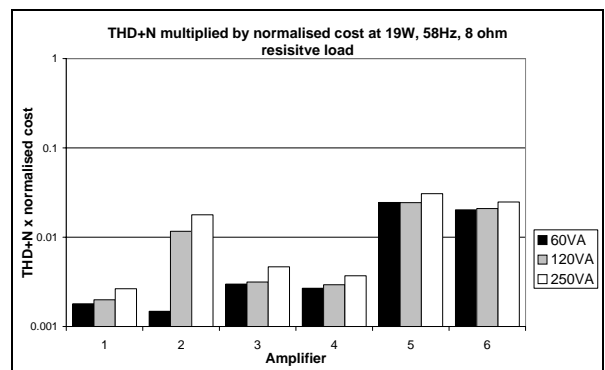


Fig. 11. THD+N multiplied by cost of amplifiers. Measured at 58Hz, outputting 19W into an 8Ω resistive load. Measured with unregulated power supplies.

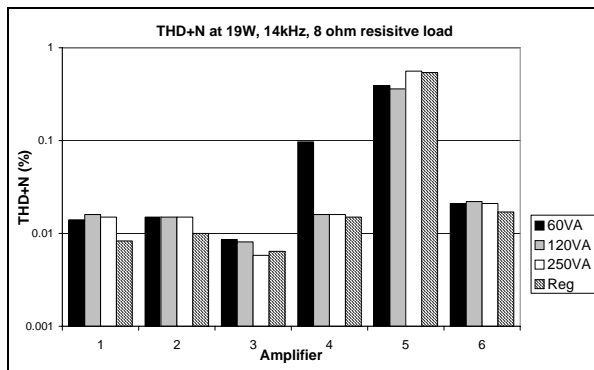


Fig. 9. THD+N of amplifiers at 14kHz outputting 19W into an 8Ω resistive load. Measured with all power supplies.

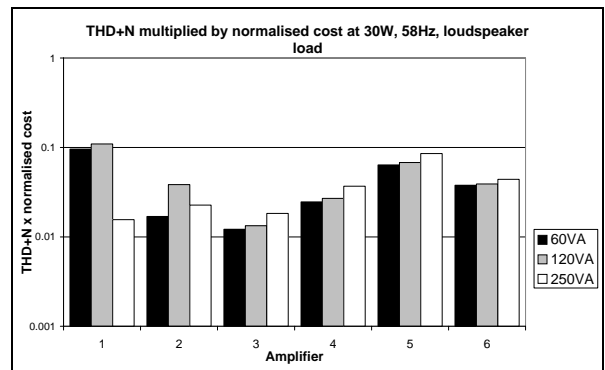


Fig. 12. THD+N multiplied by cost of amplifiers. Measured at 58Hz, outputting 30W into the loudspeaker load. Measured with unregulated power supplies.

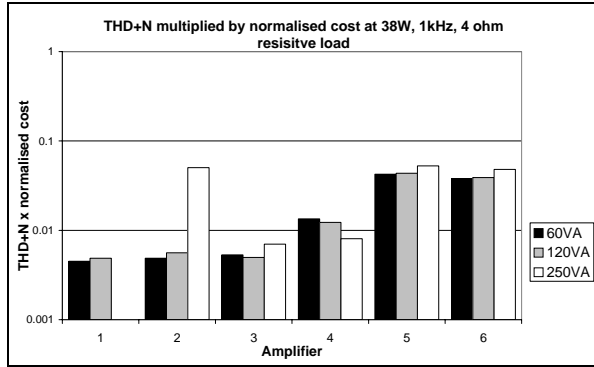


Fig. 13. THD+N multiplied by cost of amplifiers. Measured at 1kHz, outputting 38W into a 4Ω resistive load. Measured with unregulated power supplies.

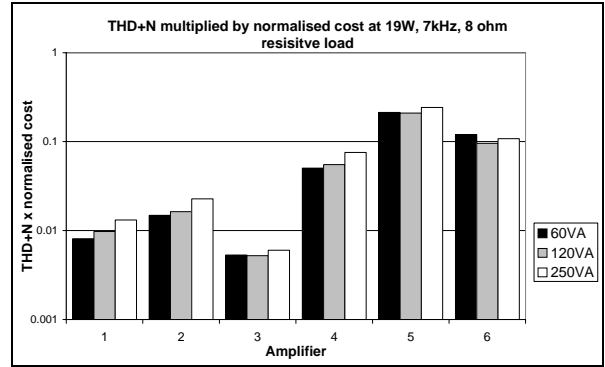


Fig. 16. THD+N multiplied by cost of amplifiers. Measured at 7kHz, outputting 19W into an 8Ω resistive load. Measured with unregulated power supplies.

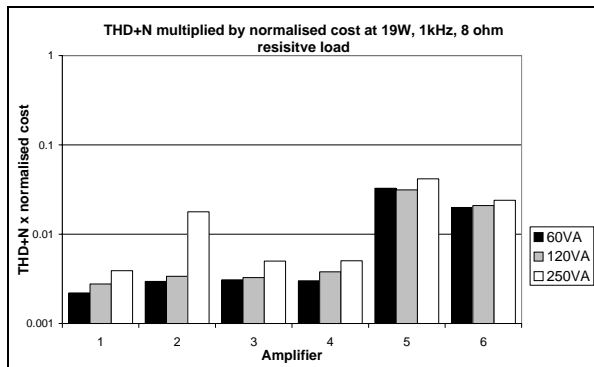


Fig. 14. THD+N multiplied by cost of amplifiers. Measured at 1kHz, outputting 19W into an 8Ω resistive load. Measured with unregulated power supplies.

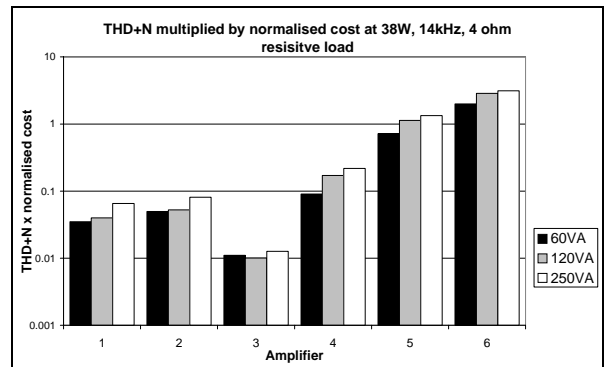


Fig. 17. THD+N multiplied by cost of amplifiers. Measured at 14kHz, outputting 38W into a 4Ω resistive load. Measured with unregulated power supplies.

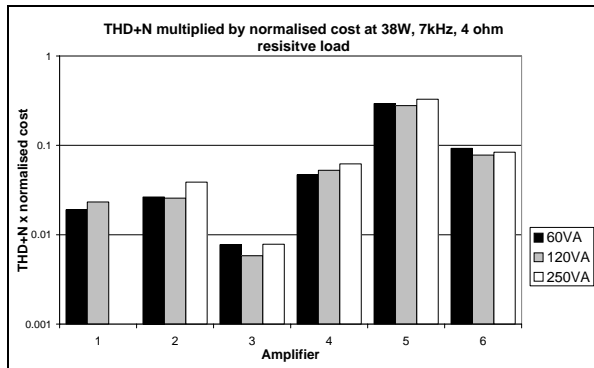


Fig. 15. THD+N multiplied by cost of amplifiers. Measured at 7kHz, outputting 38W into a 4Ω resistive load. Measured with unregulated power supplies.

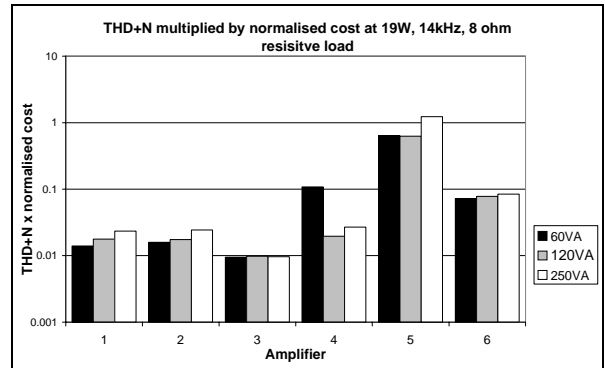


Fig. 18. THD+N multiplied by cost of amplifiers. Measured at 14kHz, outputting 19W into an 8Ω resistive load. Measured with unregulated power supplies.