Chapter 1

Introduction

Fundamentally, only little has changed in the final stages of the audio reproduction chain for decades. The electrodynamic transducer as invented by C.W. Rice and E.W. Kellog in 1925 still forms the basis for the majority of loudspeakers in use today and the principle has only seen marginal changes within nearly 75 years. The widespread use can not be justified by superior performance, in fact the principle of electric-acoustic conversion is limited by numerous fundamental problems, that makes this ultimate stage in the audio chain the weakest – by far. One essential limitation is the striking inefficiency. Generally, a given amount of acoustic power requires orders of magnitude higher power input delivered by the power amplifier. The power amplifier has the task of amplifying the audio signal to a level that, combined with sufficient current to move the coil, produces the desired acoustic level from the loudspeaker. The poor loudspeaker efficiency is very unfortunate, since power amplifiers generally have to be capable of delivering large amounts of undistorted power, to produce the subjective levels demanded by the consumer.

The field of audio power amplification has equally suffered from a lack of real break-through inventions for decades. Thus, sound reproduction today is founded on a few power amplifier principles that are characterized by a linear operation of the output transistors. The advantages include topological simplicity and good performance, but the linear amplifier principles suffer from low efficiency, which is critical since the power amplifier handles considerably amounts of power. Accordingly, power amplifiers are in general provided with massive heat sinks of extruded aluminum to cope with the heat development. Negative side effects of inefficient power amplification include high volume, weight, cost and reliability problems. Moreover, the power amplifier has low energy utilization, which is clearly not an attractive feature in this energy-conscious area.

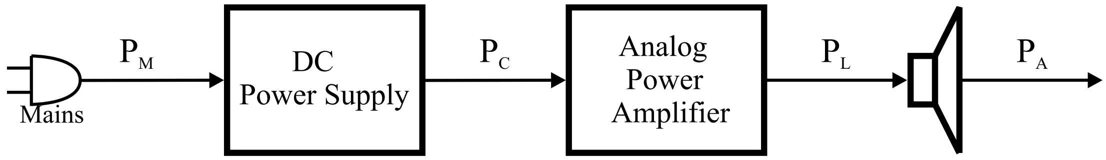


Fig. 1.1 Power flow in audio reproduction chain.

Consider the model of essential power flow in a typical audio system, shown in Fig. 1.1. To illustrate the low power utilization, a typical 100W power amplifier is considered. The power flow at two specific output levels is given below.

Situation	P_M	P_C	P_L	P_A
Typical	15W	10W	100mW	1mW
1/3 of max.	115W	90W	30W	300mW

Clearly, the transducer is the fundamental source of the efficiency problems, i.e. an efficiency improvement by and order of magnitude would virtually eliminate the need for power amplification, as we know it today. However, most of the power is dissipated in the *power amplifier* due to low efficiency in this stage.

The primary objective of the research resulting in the present dissertation has been to invent practical power amplification methods with *significant* improvements in efficiency at all levels of operation – without any compromises on audio performance. Improving power amplifier efficiency isolated will have significant influences on overall system efficiency, especially at lower levels of operation where much can be gained.

It might seem paradoxical, that this level of efficiency is tolerated in the industry, especially since a low efficiency only has negative side effects. There are several answers to this apparent paradox. Principles for more high efficiency power amplification – so called Class D or swithing power amplifiers - have been known for decades, however previous findings have shown several problems in terms of achieving the e.g. desired efficiency and audio specifications. On the other hand, methods to achieve sufficient levels of performance with linear power amplification are well known, and linear power amplification have over several decades of time established a reputation for good quality. A second problem is, that the audio community is highly conservative, often dominated by religious belief rather that scientific documentation and objective evaluation. Furthermore, only few have been interested in environmental issues despite the potential for dramatic improvements. Finally, amplifier weight, volume and energy consumption (!) has actually been considered a quality parameter (the larger and heavier the better), although there has never been any scientific documentation for any correlation between sound quality and these parameters. It is to expect however, that environmental issues will also reach consumer products. A high efficiency could become an attractive parameter in the future especially since labeling or standardization in consumer electronics is on its way [Ni95].

1.1 Audio power stage topologies

A brief introduction to commonly used circuit techniques for audio power amplification is given in the following with focus on their efficiency characteristics. It is common to differentiate between the different amplifier principles are by their *class.* A list of used

Class	Characteristics
A	Conducts signal current throughout the cycle of the signal waveform (360^0 conduction)
B	Conducts signal current exactly for one-half of the cycle of the input-signal waveform (180^0 conduction)
AB	Class B with bias to avoid crossover distortion.
C	<180^0 conduction with resonant loading. This method is primarily for RF frequency, and is only rarely used in the audio frequency range.
D	0^0 conduction. The power stage transistors are switched which in theory prevents the system from entering the active region.
B2, G, H	Extension of class B where more complex power supply circuitry is used to improve efficiency.

Fig. 1.2 Amplifier techniques reviewed.

classifications is listed in Fig. 1.2, with a short description of the characteristics [Be88]. The Class AB and B output stage topology, shown in Fig. 1.3 (top), forms the basis for the majority of power amplifiers today, and design techniques to realize high quality class B amplifiers have been known for decades. However, since the output voltage is derived form the supply voltage via the output transistors, it follows that the difference between the output voltage and the rail voltage must be dropped *across* the output transistors. This results in a wasteful dissipation of energy in the output transistors. The effective voltage drop across the output stage transistors can be reduced by the complex class B2 or class G configuration shown in Fig. 1.3.

1.1.1 Power and energy efficiency

Since amplifier efficiency is an essential parameter throughout the thesis, the efficiency of the most widely used power amplifier principles is investigated and compared. It is trivial to derive analytic expression for the efficiency vs. relative output level as shown in Appendix A for the three amplifier principles. The *power efficiency* is the ratio of utilized power over the supplied power:

$$\eta_P(x) = \frac{P_L(x)}{P_S(x)} \tag{1.1}$$

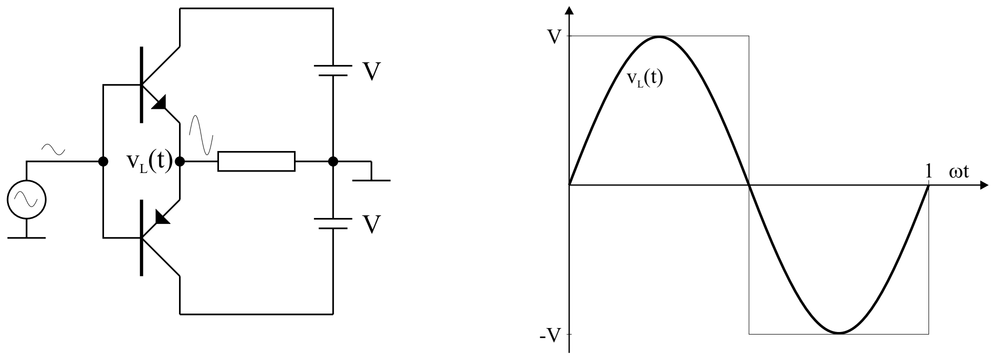
Where x denotes the relative output level. The amplifier output power is:

$$P_L(x) = x^2 \frac{V^2}{2R_L} \tag{1.2}$$

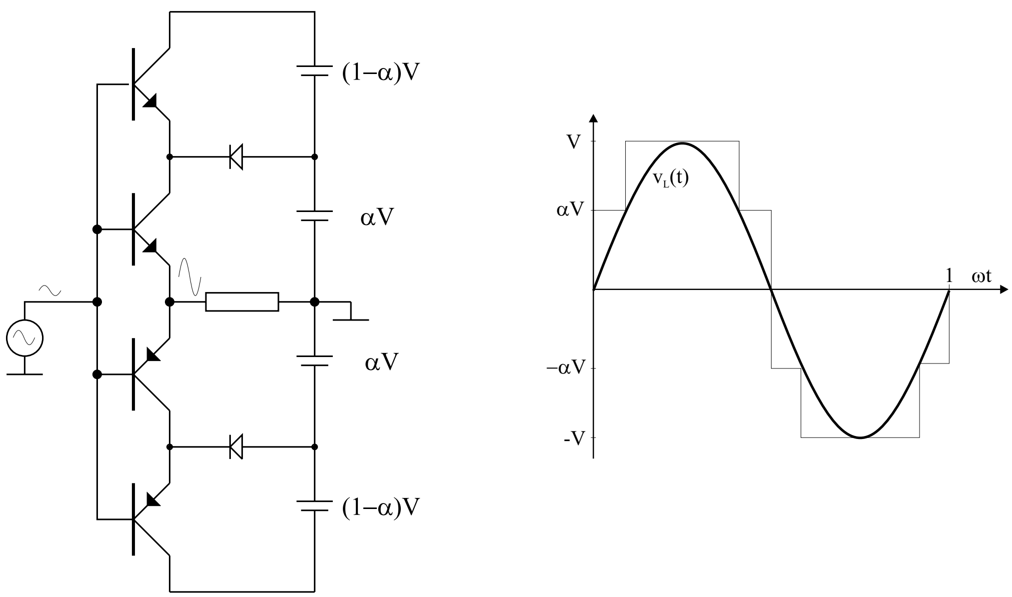
As shown in appendix A, the efficiency for the three output stage configurations are:

$$\eta_B(x) = x\frac{\pi}{4} \tag{1.3}$$

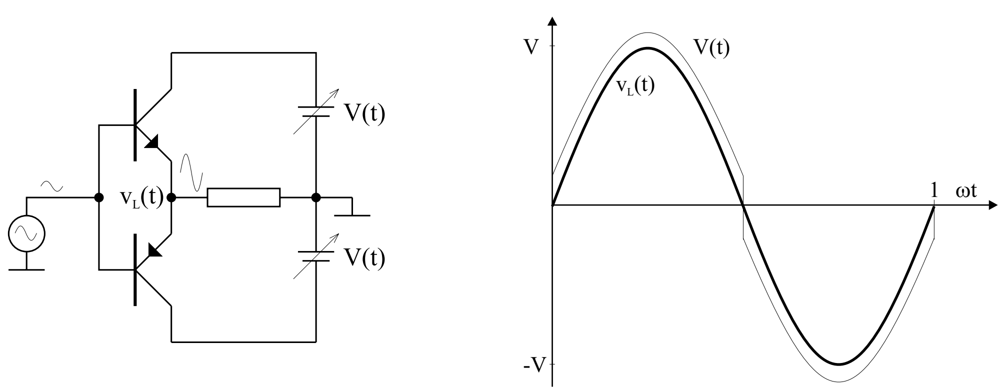
$$\eta_{B2}(x,\alpha) = \begin{cases} \dfrac{\pi}{4}\dfrac{x}{\alpha} & (x < \alpha) \\ \dfrac{\pi}{4}x\dfrac{1}{\alpha + (1-\alpha)\int_{\alpha\sin(\frac{\alpha}{x})}^{\frac{\pi}{2}} \sin(\omega t)d(\omega t)} & (x \geq \alpha) \end{cases} \tag{1.4}$$



Class B



Class B2



Class G

Fig. 1.3 Three widely used output stage configurations Class B, Class B2 and Class G.

$$\eta_G(x,\beta) = x\frac{\pi}{4}\left(\frac{1}{\beta + x\frac{\pi}{4}}\right) \tag{1.5}$$

Fig. 1.4 shows the ideal efficiency vs. relative output level for the three amplifier principles, and Fig. 1.5 equally shows the relative power dissipation vs. x. Class B2 and G and achieve reasonable efficiencies at higher output powers, but all topologies still have significant power dissipation at all output levels. In more aspects, these idealized models are not sufficient to estimate the real output stage efficiency especially at lower output levels. There are practical limitations further decreasing the efficiency of the output stage topologies, such as the necessary quiescent current to linearize the output stage and the saturation voltages in the output stage transistors. Subsequently, more realistic models of the three output stage topologies have been investigated that incorporate these important effects. Fig. 1.6 and Fig. 1.7 shows the efficiency and relative power dissipation of these more realistic output stage topologies. Note how the typical efficiency of all topologies is extremely low, primarily due to the significant power loss at quiescence.

1.1.2 Energy efficiency considerations

There is only little correlation between power efficiency and the amplifier energy consumption, since the power efficiency is typically specified at the level of maximal power dissipation or at the maximal output level. An alternative efficiency measure - the energy efficiency - is defined in the following. The basis is investigations of the general consumer behavior in terms of an average time distribution of volume control positions. Such a distribution will vary as a consequence of e.g. loudspeaker sensitivity, room size, user age and numerous other parameters. However, it is possible to generalize [Ha94b] and define four subjective listening levels as given in Table 1.1. The distribution should be interpreted as: In 89% of the time, the average user listens to background music with an average output level of -40dB etc. Since the distribution might vary dependent on application (e.g. in professional systems the distribution would be different), a general time distribution is considered:

$$(n_1, P_{L,1}, P_{S,1}), (n_2, P_{L,2}, P_{S,2}), \ldots (n_N, P_{L,N}, P_{S,N}) \tag{1.6}$$

$(n_j, P_{L,j}, P_{S,j})$ refers to that the output power in average is $P_{S,j}$ in n_j percent of the time and $P_{S,j}$ refers to the supplied power at the given output power. The *energy efficiency* is derived as the ratio of the average output power and the average supplied power:

$$\eta_E = \frac{\sum_{i=1}^{N} n_i \cdot P_{L,i}}{\sum_{i=1}^{N} n_i \cdot P_{S,i}} \tag{1.7}$$

Distribution in time	Output level (rel.)	Subjective level
0 %	0 dB	Clipping
1 %	-9 dB	Party
10 %	-24 dB	Listening
89 %	-40 dB	Background

Table 1.1 Average time distribution of volume control positions.

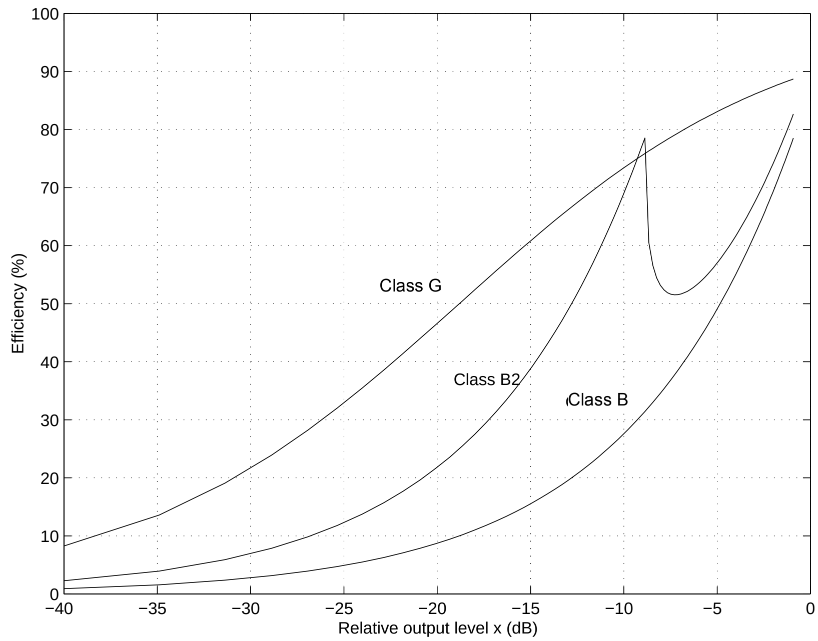


Fig. 1.4 Efficiency vs. relative output level for ideal power amplifier output stages.

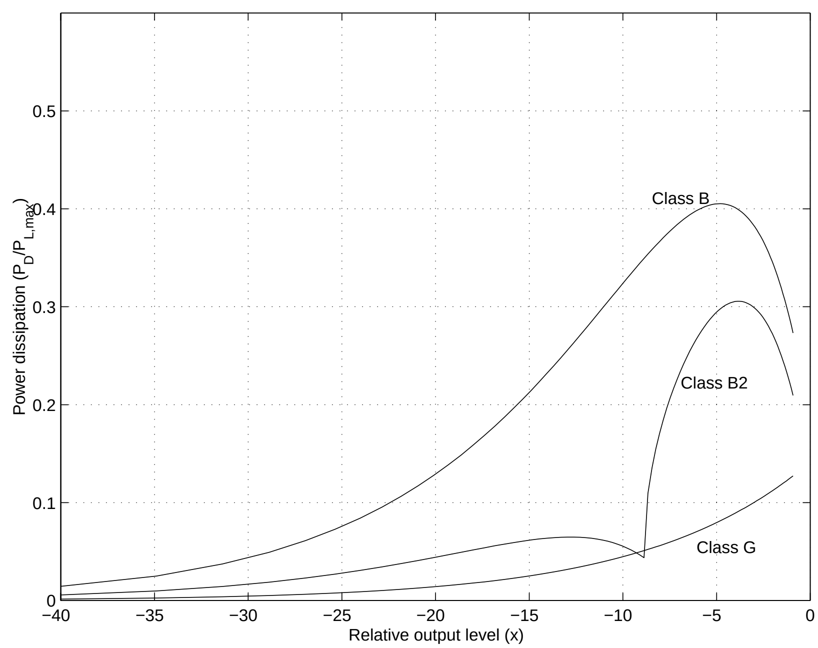


Fig. 1.5 Power dissipation vs. relative output level for ideal power amplifier output stages.

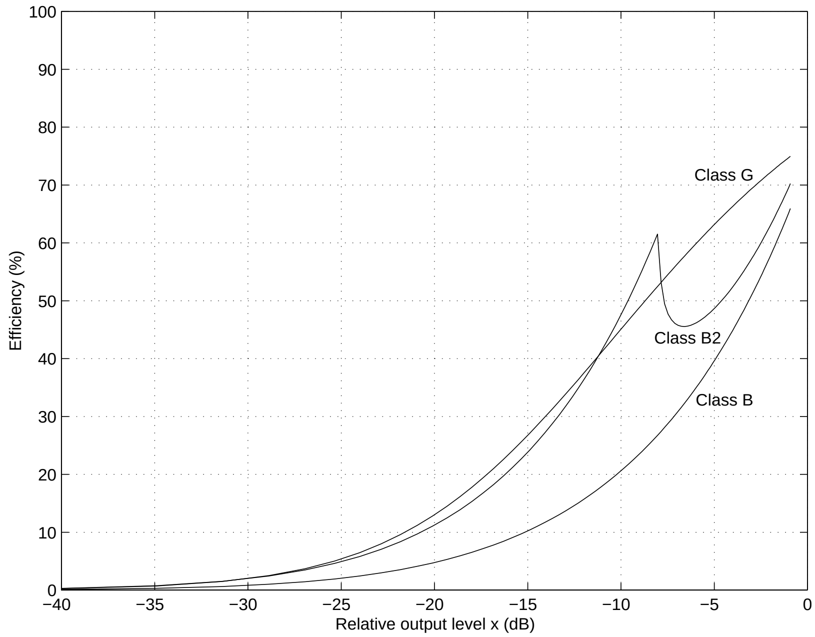


Fig. 1.6 Efficiency and power dissipation for realistic models of class B, B2 and G power amplifier output stages topologies.

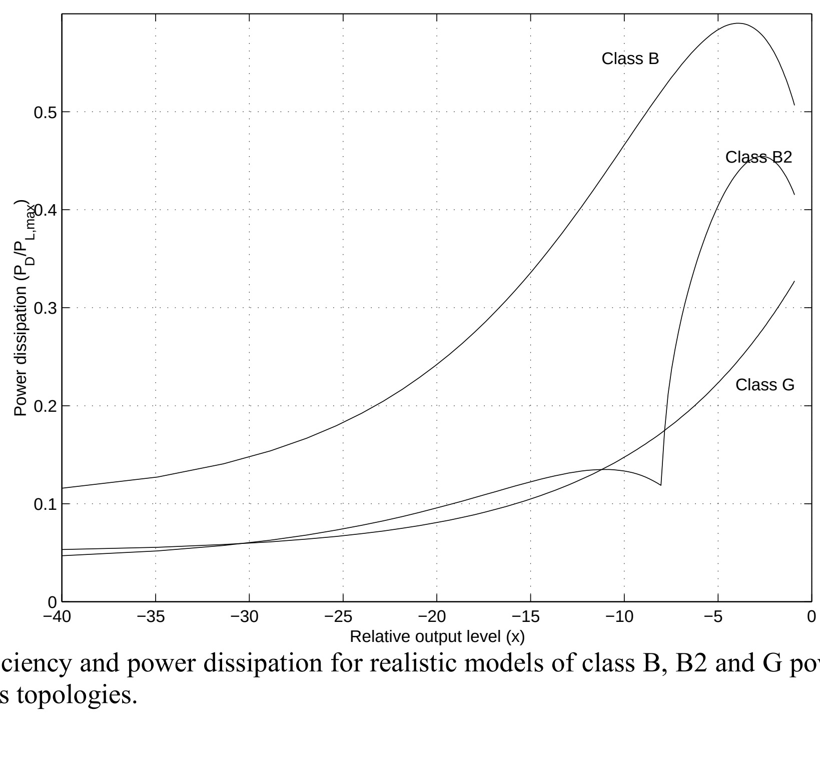


Fig. 1.7 Efficiency and power dissipation for realistic models of class B, B2 and G power amplifier output stages topologies.

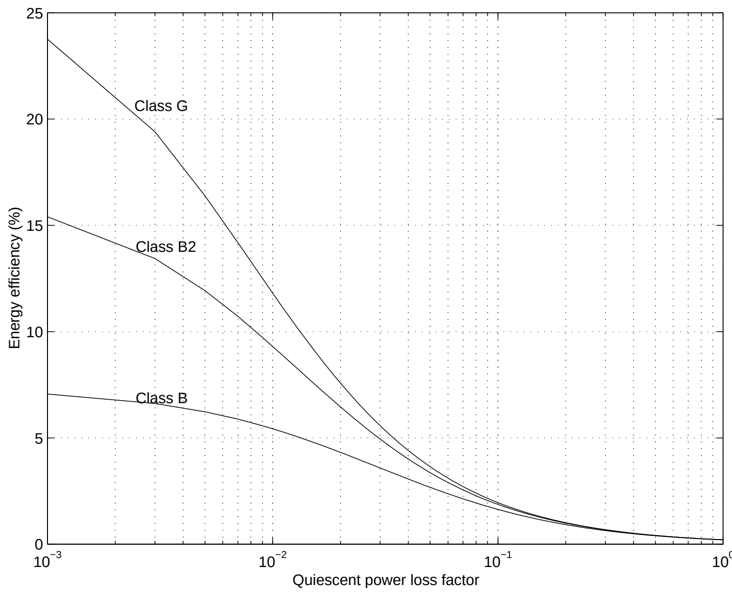


Fig. 1.8 Energy efficiency of Class B, Class B2 and Class G.

The parameter can be used to minimize the energy consumption in any system. Let the *quiescent power loss factor* λ be defined as:

$$\lambda = \frac{P_S(0)}{P_{L,\max}} \tag{1.8}$$

Fig. 1.8 illustrates the energy efficiency for the realistic models of class B, B2 and G power output stages, as a function of λ. The typical energy efficiency for a class B output stage is only:

$$n_E \cong 1 - 2\% \tag{1.9}$$

This holds for λ between 0.1 and 0.2, which is typical for a class B output stage. Note that the energy efficiency for an *ideal* class B amplifier is only 7.1%, due to the inherent losses bound to the linear operation of the output transistors. Since the power amplifier operates in the "background music" mode most of the time, the important parameters in terms of energy efficiency are not surprisingly the power dissipation at low output levels and especially the quiescent power dissipation. The energy efficiency of class B2 and class G can be made considerably better (see Fig. 1.8) if the λ is sufficiently low. However, this is not easy to obtain in any of the two alternatives. For class B2, lowering α will compromise the efficiency at higher output levels (no gain compared to class B) and for class G, the switching power supplies will cause the quiescent power loss λ factor to be high. To conclude, all output stages have their limitations, and more than a doubling in energy efficiency by optimization cannot be expected.

1.1.3 The switching (Class D) power stage topology

Based on this initial investigation of output stage topologies it is concluded that considerable improvements in efficiency cannot be achieved with output transistors operating in the linear range. A completely switching power stage is needed. This approach

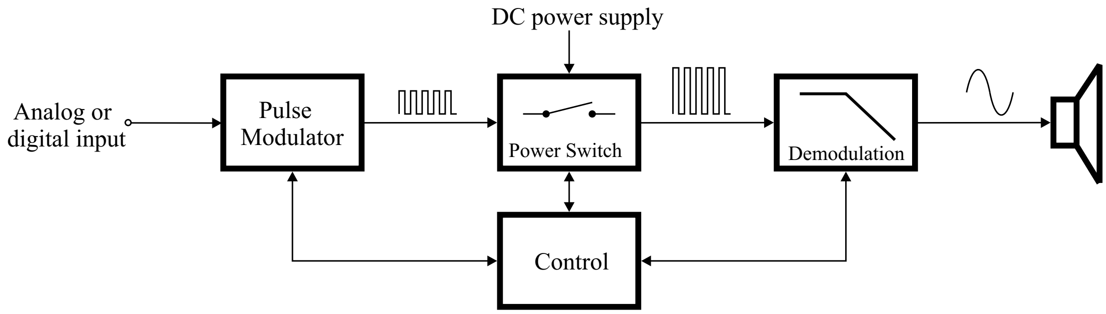


Fig. 1.9 General Pulse Modulation Amplifier (PMA) utilizing a class D power stage.

has the inherent advantage of a 100% theoretical efficiency. With the continuing improvements in power switching devices, the efficiency will converge towards this theoretical optimum as time progresses. Throughout the years the fundamental principle of power amplification using switching technology has been called class D, switching power amplification, digital power amplification and PWM power amplification. Recently, what is believed to be a more suitable and general designation – Pulse Modulation Amplifiers (PMA) – has been introduced by the author [Ni97a]. This general designation will be used henceforth.

1.2 The Pulse Modulation Amplifier (PMA)

Fig. 1.9 shows the general PMA topology. The four fundamental blocks are the *pulse modulator*, the *switching power stage*, the *demodulation filter* and the *error correction* block. The pulse modulator may be based on either analog or digital pulse modulation techniques, correspondingly referenced to as analog PMA and digital PMA systems. The power switch converts the pulse modulated signal to power level. Following, the power pulse modulated signal is feed to a filter to reconstitute the modulated signal. The control system serves to compensate any errors that are introduced in each of the three essential blocks of the system.

The pulse modulator is the heart of the PMA system. Two analog pulse modulation methods for PMAs are PWM and PDM, shown in Fig. 1.10. The methods may be implemented in both the analog and digital domain. The modulator output generally contains three distinct elements:

- The modulated signal.
- Distortion components related to the modulated signal.
- A high frequency spectrum.

The high frequency output is composed of either discrete components related to the carrier, noise shaped noise or a combination of both. The pulse modulator can be based any scheme performing a coding of the modulating signal to a pulse modulated form. One of the objectives of this thesis is to research in coding schemes that provides optimal PMA performance.

Power amplification based on pulse modulation techniques in combination with a switching class D power stage have been known for decades. Some of the first designs were already presented by e.g. Sinclair and Johnson [Jo67], [Jo68] some 30 years ago. However, until recently the research has been quite modest with only a few noteworthy publications as e.g. [At83], [Ha91]. Within the last decade, the field has "resurrected" now with focus on digital pulse modulation methods for digital PMA systems. An exhaustive

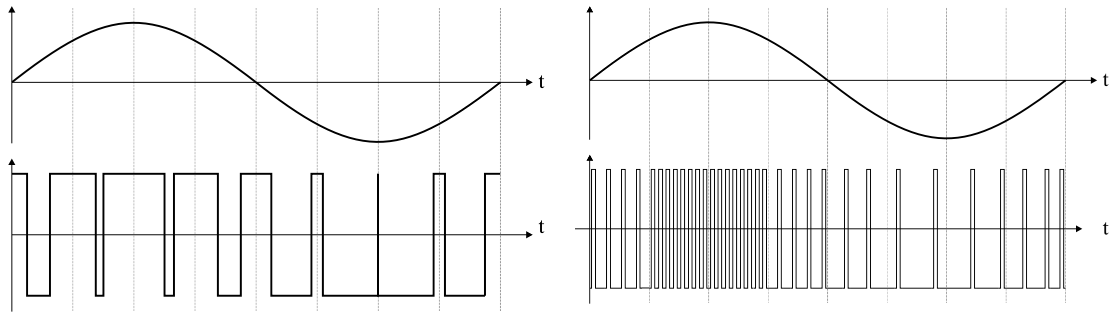


Fig. 1.10 PWM and PDM pulse modulation methods.

set of publications exists on this specific subject, e.g. [Sa86], [Le91], [Go91], [Go92], [Ha92] and [Hi94]. The digital PMA approach was considered a break-through in audio power amplification. Nevertheless, it has proven very difficult to realize the acceptable audio performance in both analog PMA and digital PMA system. The problems relate to the non-linear power conversion and demodulation.

1.2.1 Design problems and challenges

PMA systems and audio power amplifiers in general are complex non-linear systems. Thus, power amplifiers are subject to varying input signals, generally drive reactive loads, are most often supplied by non-regulated power supplies which supply the other channels for sound reproduction. Furthermore, power amplifiers might be subjected to overload situations if not prevented. No power amplifier can be optimized without a simultaneous consideration of a broad range of desired specifications. Furthermore, the tolerance of these specifications has to be considered. The essential issues to consider when designing and evaluating power amplifier systems are outlined below.

Gain

A specification of the insertion gain of the system typically specified in dB.

Frequency response / Bandwidth

The ability of amplifier to amplify signals over a range of frequencies, with defined source and load. Specifications are generally a –3dB bandwidth, and a tolerance on the deviation from the desired response at any frequency up to the bandwidth limit.

Harmonic distortion / Intermodulation distortion

The non-linear behavior of the amplifier causes harmonic distortion (THD) and intermodulation distortion (IMD). Moreover, the distortion will in general depend on parameters as signal level, frequency and load parameters. Distortion has to be well controlled within this parameter space. Distortion is normally specified in percentage or dB. Various IMD measurement methods exist as the two-tone CCIF, SMPTE or Transient Intermodulation Distortion (TIM).

Noise / Signal-to-noise ratio / Dynamic range

All amplifiers have internal noise sources that contribute to the output noise. Typical specifications are the residual noise referred to the output with terminated input or the Signal-to-noise ratio relative to a given output level e.g. 1W. Also frequently used is the dynamic range, which is the relationship between the maximal RMS voltage output before clipping and the RMS of the residual noise.

Output impedance / Loading

The load impedance is generally frequency dependent with resonant peaks etc. The influences of a variable load in system frequency response should be minimized. Furthermore, the amplifier output impedance should be as low as possible to cope with variations in nominal load impedance.

Power Supply Rejection

The power amplifier has to cope with the inevitable power supply perturbations. The amplifier should be able to suppress these perturbations such that the output is not influenced. A widely used specification is the power supply rejection ratio (PSRR), which is the sensitivity of the output to perturbations on the power supply. The rejection of such perturbations has to be controlled over the complete bandwidth.

Stability

A control system is generally required to secure robust performance for the power amplifier. This introduces a potential risk of instability. The amplifier should be prevented from instability under all circumstances, since this will generally have dramatic consequences as a burn out of the speaker of the amplifier itself.

There are no definitive margins between what is required to be acceptable and unacceptable. However, a set of parameters corresponding to satisfying performance in most applications can be specified:

Parameter	Condition	Value
Bandwidth	-3dB	> 60KHz
Power bandwidth	-3dB	> 20KHz
Frequency response	20Hz – 20KHz	<± 0.2dB
THD	@ 1W / 1KHz	< 0.01 %
THD	20Hz-20Hz (complete range)	< 0.05 %
IMD	CCIF two tone	< 0.01%
SNR	A weighted @ 0dBW	>90 dB
Dynamic range	A weighted	> 110dBA
Load range		2-16 Ω
PSRR	All frequencies	> 40dB

A power amplifier with a reasonable power handling capability (e.g. 100W) is considered.

1.2.2 Other considerations

The application range for high efficiency power amplification is very broad. Active speaker systems with dedicated speakers and power amplifiers for each frequency band is a specifically interesting application. This enclosed environment offers some special advantages:

- The load and amplifier can be matched perfectly. Load variations (typically 2, 4 and 8 ohms) do not have to be considered.
- Connection wires from amplifier to speaker can be minimized.
- Bandwidth limited amplification can be utilized to optimize the efficiency.

The general spectral amplitude distribution of music material only emphasizes that the technology has certain advantages in active speaker systems. Almost independent of music material, the average acoustic power in the tweeter band 4KHz – 20KHz is much lower

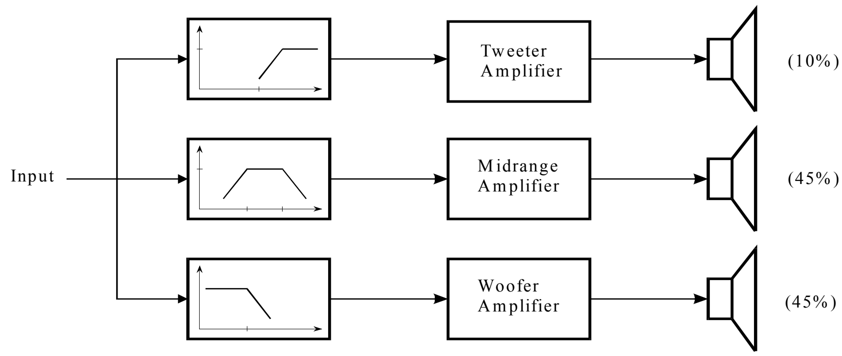


Fig. 1.11 An active speaker system (here 3 way) based on separate amplifiers for each band.

than in the other bands. Fig. 1.12 illustrates a more specific analysis. This will be reflected in the power amplifier size for each band as illustrated with a typical active 3-way speaker system in Fig. 1.11. Thus, the power handling capability is only around 10-15% of the total power in the tweeter band. Optimization of energy efficiency in active speaker systems can as such be carried out by improving efficiency in the lower 20% of the frequency band only. In this particular environment, the PMA design challenge is clearly somewhat different from the general case.

1.3 Thesis structure

The primary objective of the research resulting in the present dissertation has been to invent practical power amplification methods with significantly improved efficiency at all levels of operation – without any compromises in terms of audio performance. It will become apparent when reading the thesis, that this has required multi-disciplinary research involving such diverse fields as e.g.; analog and digital modulation theory, power electronics, DSP, semi-conductor physics and control systems.

The thesis is divided in two volumes, the main part consisting of 11 chapters divided in four parts, and a second volume consisting of the three appendices A, B and C.

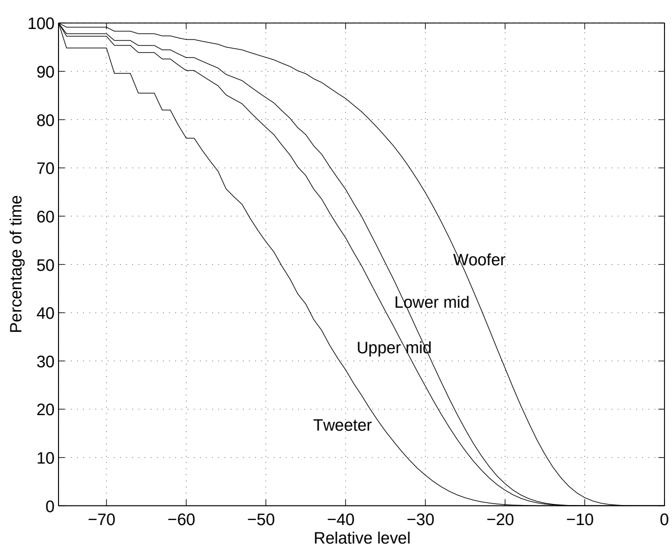


Fig. 1.12 An example of the distribution of signal levels on a CD in four bands. The bands are divided at 650hz, 1500hz and 4.5KHz. The programme material is "The Division Bell" by Pink Floyd.

Chapter 1 has introduced the motivating factors and the foundation for the research.

Part I (Chapters 2-3) presents a comprehensive analysis of analog and digital pulse modulation methods suitable for analog PMAs and digital PMAs, respectively.

Chapter 2 is devoted to analog pulse modulation methods. A broad set of pulse modulations methods are subjected to a fundamental analysis of their suitability in analog PMA systems. The chapter contributes to fundamental modulation theory by introducing a novel family of modulation methods – Phase Shifted Carrier Pulse Width Modulation (PSCPWM).

Chapter 3 is devoted to digital pulse modulation methods for digital PMAs. Previously presented methods are reviewed. A simple design methodology is presented for digital PWM modulators.

Part II (Chapters 4-5) continues to the second major block of the PMA - the power stage. Power stage structures are synthesized and analyzed, and methods for optimal power stage implementation are devised.

Chapter 4 is dedicated to a fundamental analysis of error sources within PMA systems. It is shown how the power conversion stage seriously effects all the important parameters of the system, i.e. linearity, noise and efficiency. Modulator error sources are also investigated.

Chapter 5 is devoted to efficiency optimization in the power conversion stage of PMAs. Starting with a simple switching leg, the analysis extends to the general multi-level PSCPWM power stage topologies.

Part III (Chapters 6-9) continues to the third major block of the PMA – control system design.

Chapter 6 investigates the application of robust linear control to analog PMA systems. A methodology for control system design is introduced. Three fundamental linear control methods are investigated, and robust case example designs are synthesized and analyzed.

Chapter 7 is devoted the presentation of a control method, dedicated to solve the fundamental problems in analog PMA systems – Multivariable Enhanced Cascade Control (MECC).

Chapter 8 investigates the application of non-linear control methods for analog PMAs. The focus in on a new non-linear modulator/controller structure – Three level One Cycle Control (TOCC). Advantages and disadvantages compared with linear control are emphasized.

Chapter 9 is dedicated to the complex issues of error correction in digital PMA systems. A new control method for enhanced power amplification of a pulse modulated signal is presented – Pulse Edge Delay Error Correction (PEDEC). PEDEC based digital PMA topologies are presented and evaluated.

Part IV (Chapter 10) is devoted to implementation and evaluation.

Chapter 10 is dedicated to the practical evaluation of all investigated principles and topologies. Performance specifications for the various prototypes developed during the project are presented.

Chapter 11 summarizes the essence of the thesis and draws the essential conclusions.

Volume II contains three appendices:

Appendix A supplements Chapter 1. Investigations of power and energy efficiency for various amplifier concepts are carried out.

Appendix B supplements Chapter 2. Details of the derivation of analytical double Fourier series expressions for a broad range of analog pulse modulation methods are given.

Appendix C is a complete reproduction of the conference and journal papers that have been published at during the project.