Chapter 11

Summary and Conclusions

Various methods for energy efficient audio power amplification using pulse modulation techniques have been investigated in the present work. The power amplifier is generally the most energy consuming element in the audio chain with a typical the energy efficiency of only 1%, so there is much room for improvement. Furthermore, audio power amplifiers get voluminous, heavy and costly as a direct consequence of low efficiency so there are several motivating factors to research in new improved solutions. Previous research has shown that pulse modulation based amplifier systems are connected with several problems and it has been difficult to realize a sufficient level of performance. The fundamental problems have been addressed with a great deal of fundamentalism, leading to multi-disciplinary research is various scientific fields as analog and digital modulation theory, various fields of power electronics, signal processing and control system design. This ultimate chapter will summarize the essence of the work performed and emphasize the essential conclusions.

A detailed study analog pulse modulation method was carried out, founded on the Harmonic Envelope Surface (HES) as an effective tool for analysis and consistent comparison of methods. NPWM methods were concluded to be very well suited for PMA applications to the excellent linearity and simple realization, combined with simple implementation of the power conversion stage. However, the significant HF output of the fundamental schemes presents a significant problem in PMA systems. A novel class of modulation methods – Phase Shifted Carrier Pulse Width Modulation (PSCPWM) was introduced as a contribution to the field of modulation theory for PMA systems. The analysis concluded on the advantages of the double-sided balanced PSCPWM methods, BND1, BND2 and BND3, implemented in the BPSC power stage topology. Some of the proven advantages of these modulation methods include:

- An improved multi-level synthesis of the modulating signal, where the HF content of the pulse modulated output is minimized.
- A controllable increase in effective sampling frequency.
- Minimal power supply complexity (single supply).
- Reduced switching frequency in each switching leg reducing the effects of error sources.
- Improved total efficiency by a combination of reduced conduction and switching losses.

The focus turned towards digital pulse modulation methods in Chapter 3. Various enhanced digital PWM methods were reviewed and LPWM was selected on a performance / complexity scale. Previous research on LPWM was extended by a detailed investigation of both linearity and HF performance. A simple LPWM modulator design methodology was devised based on a separation of linearity and dynamic range demands. An important conclusion is, that optimized digital modulators for digital PMA systems provide excellent performance, well beyond what can be reproduced by the subsequent power conversion stages. Consequently, the digital modulator is not a limiting factor on digital PMA system performance.

The inherent error sources within the power conversion stage was addressed in Chapter 4, by studying the physical limitations within the switching devices and following investigate the effects of these limitations on PMA system performance. The error sources were separated in Pulse Amplitude Errors (PAE) and Pulse Timing Errors (PTE) and following subjected to a qualitative analysis. In was concluded that the power stage, independent on modulation method and power stage topology, is the fundamental limitation in all PMA systems. Chapter 5 extended the investigations of power conversion, by addressing efficiency optimization for the general PSC and BPSC switching power stage topologies. Case example power stage designs were presented, illustrating the excellent efficiency approaching 95% and energy efficiency in the area of 30% that can be achieved with the present stage of technology. Future development in switching power devices and magnetics will only improve these figures. The PSC and BPSC power stages proved advantageous in terms of system efficiency due to reduced total conduction and switching losses. In general, optimized PMA systems completely redefine the level of energy efficiency in power amplification. The practical evaluation of various power stage topologies verified the theoretically expected levels of power and energy efficiency.

The application of robust linear feedback control methods to analog PMA systems was the subject of Chapter 6. A design methodology for robust control system design was introduced, based on an initial study of the plant to be controlled and the uncertainty within the plant. Three fundamental linear control methods were investigated, VFC1, VFC2 and CVFC, and robust case example designs were synthesized and evaluated. The practical verification of the methods revealed that even simple linear control methods offer a remarkable value, by reducing the sensitivity to any kind of disturbance significantly. The three topologies proved to have their own advantages and disadvantages.

Chapter 7 introduced an enhanced linear control topology dedicated to PMA systems – Multivariable Enhanced Cascade Control (MECC). The topology is based on a recursive structure of loops formed as an enhanced cascade from a single or alternatively two feedback source in the MECC(N) and MECC(N,M) versions, respectively. Fundamentally, MECC offers a practical and robust method for higher order control system implementation with MECC(N) for dedicated applications and MECC(N,M) for general applications. The advantages covers e.g. flexibility in loop shaping, balanced signal levels throughout the control structure and simplicity in implementation with low requirements for the compensator blocks. This combination of features makes MECC the most powerful and flexible control method existing for general analog PMA systems. The theoretical advantages were also demonstrated in practice, by the implementation of a high power, full bandwidth analog PMA with state-of-the-art performance.

A radically different approach, in terms of a combined modulator/controller method realizing non-linear control of the PMA, was investigated in Chapter 8. The non-linear controller proved indisputable advantages over any linear control method in terms of transient response, stability and robustness to uncertainties. Unfortunately, the topology proved to have limited corrected effect and the implementation of the system illustrated further problems that are difficult to compensate for. A more fundamental and general constraint was concluded to be the difficulty in modeling and optimization of the system.

A contribution to the field of digital PMA systems was presented in Chapter 9, in terms of a new pulse reference control method for improved power amplification of the digital pulse modulated signal. The principle - Pulse Edge Delay Error Correction (PEDEC) – is proposed as a general method for enhanced power amplification of a pulse modulated signal. The introduction of a simple linear PEDEC unit control function simplifies both modeling of the principle and the practical implementation. The method was applied to digital PMAs by defining three topologies with different characteristics in terms of error estimation and feedback source. The evaluation of the topologies by simulation and practical implementation verified the functionality of the principle, i.e. PEDEC provides a significantly reduced sensitivity to towards any error within the power conversion stage. PEDEC is concluded to be a feasible method for practical, high performance digital PMA realization without a need for stabilized power supplies, tuned power stages etc.

To conclude on the present research, various methods for high efficiency power amplification has been presented to cover a broad range of applications. It has been shown that the energy efficiency can be improved by about an order of magnitude using optimized output stages. Whether to use the analog or digital PMA approach is a rather academic issue, with the solutions that have been presented for both approaches. The essence of PMA systems clearly is the revolutionary potential that lies in the unique combination of high efficiency, extreme compactness, low cost and audio specifications approaching state-of the art for power amplification – generally speaking. The present work has indicated that this delicate combination is realizable in both analog and digital PMA systems, using e.g. MECC and PEDEC, respectively. As the digital expansion continues with time, the digital PMA approach may conquer the majority of applications. In any case, with the newfound possibilities analog power amplification seems irrational from any point of view. Thus, it is to expect that high efficiency PMA systems will invade the complete application range of audio power amplification within a foreseeable time. It is hoped that the contributions to the field within this work will help to catalyze this development.