Audio Power Amplifier Techniques With Energy Efficient Power Conversion

Volume I

Ph.D. Thesis

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Preface

This thesis is submitted to the Technical University of Denmark in partial fulfillment of the requirements for the Doctor of Philosophy degree (PhD degree). The work has been carried out at the Department of Applied Electronics, DTU (until 1/12-1997 Institute of Automation) and at Bang&Olufsen A/S, Denmark during the period April 1. 1995 to April 30. 1998. The project has involved four cooperating parties: Department of Applied Electronics, Bang&Olufsen A/S, CETEC and The Danish Energy Agency. All parties are thanked for the optimal working conditions in the project.

After receiving the M.Sc.E.E. degree in October 1994 at the Technical University of Denmark, I was recommended for the present project by assoc. professors Michael A. E. Andersen and John. Aa. Sørensen. I am deeply grateful for the confidence that made my participation in this exiting project possible. Michael A. E. Andersen has functioned as main supervisor in the project, and is thanked for the never failing support, and for sharing his knowledge in power electronics.

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Abstract

The audio power amplifier pays an essential role in every system that generates audible sound. General power amplifies are voluminous, heavy, expensive, unreliable and have very poor energy utilization, all due to a low efficiency. Solutions to this very fundamental problem are the topic of the present thesis. The ultimate goal is to develop practical methods for power amplification with a significantly higher efficiency at all levels of operation without compromises on the audio performance. The problem is addressed by investigating new methods for efficient power amplification using pulse modulation techniques. A general *Pulse Modulation Amplifier* (PMA) consists of a pulse modulator (analog or digital), a switching power stage for power conversion and a control system.

A fundamental study of both analog and digital pulse modulation methods is carried out. A novel class of multi-level pulse modulation methods - *Phase Shifted Carrier Pulse Width Modulation (PSCPWM)* - is introduced and show to have several advantageous features, primarily caused by the much improved synthesis of the modulating signal. Enhanced digital pulse modulation methods for digital PMA systems are investigated, and a simple methodology for digital PWM modulator synthesis is devised. It is concluded, that the modulator performance is not a limitation in the system, regardless of the domain of modulator implementation.

Power conversion in PMA systems is addressed from the perspectives of both linearity and efficiency optimization. Based on detailed studies of the distortion mechanisms in the power conversion stage it is concluded, that this is the fundamental limitation on system performance due to several physical limitations. The analysis of general power stage efficiency concludes that dramatic improvements in energy efficiency are possible with PMA systems that are optimized for efficiency.

Control systems have been a focal point in the research. A control system design methodology is devised as a platform for synthesis of robust control systems. Investigations of three fundamental control structures show that even simple control systems offer a remarkable value, although the considered topologies also have their limitations, which is verified by practical evaluation in hardware. A novel control method is introduced - *Multivariable Enhanced Cascade Control (MECC)*. Essentially, the topology offers a practical method for higher order control system implementation by an enhanced cascade structure. MECC provides flexible control over all essential system parameters and is furthermore simple in realization. Practical evaluation of a MECC based PMA shows state-of-the-art performance.

The application of non-linear control methods is investigated with the introduction of an enhanced non-linear control/modulator topology. Although the non-linear controller is theoretically interesting, the method proves to suffer from various practical limitations.

As a contribution to the field of digital PMA systems, a novel pulse referenced control method – *Pulse Edge Delay Error Correction (PEDEC)* – is introduced for enhanced amplification of an already pulse modulated signal. The principle proves to force equivalence between the digital modulator output and the digital PMA output. PEDEC is believed to be the first documented method for practical, efficient and high quality digital PMA realization including compensation for the non-linear power conversion.

Resumé på dansk

Audio effektforstærkeren er en helt grundlæggende komponent overalt hvor der skal laves hørbar lyd. Generelle effektforstærkere er volumiøse, tunge, kostbare og har tillige en meget dårlig energivirkningsgrad, altsammen som følge af en dårlig effektivitet. Løsninger på dette helt fundamente problem er emnet for denne afhandling. Målet med projektet er således at udvikle pratiske metoder til effektforstærkning med et signifikant lavere effekttab i alle brugssituationer uden at kompromitere kvaliteten. Problemet angribes ved at undersøge nye methoder for effektiv effekforstærkning baseret på pulsmodulations-teknikker. En generel *Pulse Modulation Amplifier* (PMA) er opbygget af en puls modulator (analog eller digital), en switchende effektsomsætningsenhed og et reguleringssystem.

En fundamental analyse analoge og digitale pulsmodulationsmetoder gennemføres. En ny klasse af multi-niveau pulse bredde modulation methoder - *Phase Shifted Carrier Pulse Width Modulation (PSCPWM)* – introduceres herunder og viser at have flere fordelagtige egenskaber, primært skabt som følge af den meget forbedrede synthese af det modulerende signal. Metoder til realisering af digital pulsmodulation undersøges endvidere, og der udvikles en simpel design metodologi til digital PWM modulator syntese. Det konkluderes generelt, at modulatoren ikke er en begrænsning i systemet uanset hvilket domæne der vælges for implementeringen.

Effektomsætning til PMA systemer analyseres udfra såvel et linearitets- og effektivitets-perspektiv. På basis af detaljerede analyser af forvrængningskilder i effektomsætningen konkluderes det at dette element er den væsentlige begrænsning is systemet, som følge af en række fysiske begrænsninger. Analyserne af udgangstrin omfatter også en generaliseret teoretisk analysis af effektiviten i effektomsætningen. Det komkluderes, det der kan opnås dramatiske forbedringer i energi effektivitet i PMA systemer optimeret mht. effektivitet.

Reguleringsmetoder udgør en helt central del af undersøgelserne. En metodologi til design af reguleringmetoder introduceres som en platform for syntese af robuste reguleringssystemer. Der undersøges tre basale reguleringstopologier, og det konkluderes at selv simple reguleringssystemer giver markante forbedringer af PMA systemet, selvom en evaluering af de tre metoder i hardware viser visse begrænsninger. Et nyt generelt reguleringsprincip introduceres – *Multivariable Enhanced Cascade Control (MECC)*. Princippet er en praktisk fremgangmåde til realisering af højere orders reguleringssystemer under anvendelse af en *enhanced cascade* struktur. MECC giver flexibel kontrol over all væsentlige system parametre og er envidere simpel mht. realisering. Praktisk evaluering af en MECC baseret system viser state-of-the-art specifikationer.

Anvendelsen af ikke-lineære reguleringssystemer undersøges, ved introduktionen af et ikke lineært reguleringssystem der også fungerer som modulator. Til trods for teoretiske interessante egenskaber, viser metoden sig at lide under væsentlige fysiske begrænsninger.

Som et bidrag til området digitale PMA systemer, præsenteres en ny puls refereret reguleringsmetode – *Pulse Edge Delay Error Correction (PEDEC)* – for forbedret forstærkning af et allerede pulse moduleret signal. Det vises at at princippet fremtvinger ækvivalens mellem det puls modulerede indgangssignal og udgangssignalet. PEDEC menes at være den første dokumenterede methode for praktisk og effektiv realisering af højkvalitets digitale PMA systemer, der inkluderer kompensation for den ikke lineære effektomsætning.

List of Abbreviations

The thesis defines a range of important abbreviations to ease the discussion and comparison of principles and methods. The abbreviations are described below for reference.

Abbreviation	Description
PMA	Pulse Modulation (power) Amplifier. General definition of a system where the amplification is based on pulse modulation techniques and a switching power conversion stages. There are two alternatives: *Analog PMA* or *Digital PMA* referring to the use of analog or digital pulse modulation techniques.
NADS	Natural sampling – AD – Single Sided
NBDS	Natural sampling – BD – Single Sided
NADD	Natural sampling – AD – Double Sided
NBDD	Natural sampling – BD – Double Sided
UADS	Uniform sampling – AD – Single Sided
UBDS	Uniform sampling – BD – Single Sided
UADD	Uniform sampling – AD – Double Sided
UBDD	Uniform sampling – BD – Double Sided
LADS	Hybrid sampling – AD – Single Sided
LBDS	Hybrid sampling – BD – Single Sided
LADD	Hybrid sampling – AD – Double Sided
LBDD	Hybrid sampling – BD – Double Sided
PSCPWM	Phase Shifted Carrier Pulse Width Modulation.
MLCPWM	Multiple Leveled Carrier Pulse Width Modulation
NS / US	Naturally sampled Single Sided PSCPWM
ND / UD	Naturally sampled Double Sided PSCPWM
BNDX / BUDX	Balanced – Naturally/Uniformly sampled Double Sided PSCPWM
BNSX / BUSX	Balanced – Naturally/Uniformly sampled Single Sided PSCPWM
PSC	Power stage circuit topology for PSCPWM
BPSC	Balanced PSC power stage circuit topology for the balanced PSCPWM methods
US	Uncertainty set
NS	Nominal Stability
NP	Nominal Performance
RS	Robust Stability
RP	Robust Performance
SRI	Slew Rate Instability
VFC1	Voltage Feedback Control topology 1
VFC2	Voltage Feedback Control topology 2
CVFC	Current – Voltage Feedback Control topology
PEDEC	Pulse Edge Delay Error Correction.
PEDEC VFCX	PEDEC Voltage Feedback topology X (X = 1, 2 and 3)
TOCC	Three level One Cycle Controller
PAE	Pulse Amplitude Errors
PTE	Pulse Timing Errors