MECC—A Novel Control Method for High End Switching Audio Power Amplification

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MECC - A Novel Control Method for High End Switching Audio Power Amplification

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Abstract

The paper presents a new control topology that is dedicated to switching power amplifier systems – Multivariable Enhanced Cascade Control (MECC). MECC provides powerful and flexible control over all essential system parameters as distortion, noise, output impedance, frequency response etc. by simple means, using standard active and passive components. A 400W/4Ω MECC based power amplifier module is shown to implement state-of-the-art performance. Exceptional linearity with below -100dB (0.001%) pure THD at typical output powers is combined with >120dBA dynamic range and 93% power stage efficiency.

1. Introduction

Any power amplifier system using switching power conversion can be decomposed into three fundamental blocks: (1) the pulse modulator (analog or digital), (2) the switching power conversion stage with a passive demodulation filter and (3) the control block. A general system block diagram is shown in Fig. 1. Throughout the years this principle of power amplification using switching technology has been known as class D power amplifiers [1], PWM amplifiers [2], [4], [9] or just switching power amplifiers [7], [8]. In the case where digital pulse modulation has been investigated, digital power amplification or Power DAC has been widely used as designation for the basic topology [5], [13] in Fig. 1. Here the more general designation – *Pulse Modulation Amplifier (PMA)* will be used, as introduced in [12]. The pulse modulation may be either analog (i.e. analog PMA) or digital (i.e. digital PMA). Independent on the use of analog or digital pulse modulation, the pulse modulator output, power stage output and filter output are inherently *analog* signals, and thus sensitive to jitter, pulse amplitude distortion or any form of non-ideal behavior [15]. Subsequently, open loop operation has proven to be irrational from any point of view (performance, complexity, power supply requirements ....), and the control system is thus an essential part of any PMA system. Recently, a suite of control methods for analog PMAs were investigated in [11]. Also, control topologies specifically for high quality digital PMA systems have been presented [10], [13], [14].

This paper continues previous research with focus on *optimal* control for analog PMA systems. Ideally, a control system topology that would allow perfect control of any system parameter is desirable. The paper proposes a novel general feedback control method – *Multivariable Enhanced Cascade Control (MECC)* – that has been devised by a detailed considerations of all the specific design problems in audio power amplifier systems founded on switching technology. The objectives of the control system is to minimize all effects of non-linear behavior in terms of distortion, noise and intermodulation that are inevitably introduced within the fundamental elements of the system, i.e. the modulator, power stage or demodulation filter. Furthermore, the control system should stabilize the frequency response and the amplifier gain, and leave the system unaffected by perturbations on the power supply and variations of load impedance. The MECC topology overcomes the constraints of traditional feedback control methods, and realizes all these objectives by remarkably simple means.

2. Multivariable Enhanced Cascade Control (MECC)

MECC has two fundamental variants henceforth referred to as MECC(N) and MECC(M,N). A general block diagram for the N-loop MECC(N) topology is shown in Fig. 2, and Fig. 3 shows the extended general (N+M)-loop MECC(N,M) topology. Fundamentally, MECC is a recursive structure of N loops formed as an *enhanced cascade* from a single feedback source. MECC(N) is founded on feedback of v_p to one or several loops feeding into one or several pre-amplifier stages preceding the modulator and power switch. It may not seem obvious at first that MECC(N) should add any obvious advantages over a local feedback [8], [11]. However, it will become apparent that this simple "extension" offer significant advantages with optimized compensator realization. MECC(N) is characterized by the following distinct points:

- A *single* feedback source.
- A *single* feedback path $A(s)$ independent upon the number of loops N, providing a minimal system complexity.
- The feedback path has a *low-pass* characteristic, to filter the noise from v_p *and* compensate the demodulation filter.
- An initializing $B_1(s)$ compensator block with special characteristics.
- A *recursive* structure with a set of preferably *identical* forward path compensator blocks $B_i(s)$.

Thus, the *Enhanced Cascade* refers to these special cascade control characteristics or this dedication of the cascade to the PMA control problem. Cascade control methods have previously been applied to linear power amplifier systems, in terms of e.g. the well known Nested Differential Feedback Loop method (NDFL's) [3]. This cascade structure has some resemblance with MECC(N) in that it uses only one feedback element with a differentiating characteristic. However, differentiating the HF- feedback source v_p in this case is clearly impossible, since it would cause the feedback compensator output to produce a severe amount of HF-output with amplitudes approaching infinity (!). Cherry's motivation for developing the NDFL control method was to realize improved control of the linear power amplification stage. The motivation for developing MECC for PMA system has been similar.

The MECC(N,M) topology shown in Fig. 3 is an extension in that an additional enhanced cascade is established from v_o to one or several chained pre-amplifier stages. MECC(N,M) encloses the PMA by two *connected* enhanced cascades, providing optimized control of all system parameters as distortion, noise, output impedance, PSRR etc. The connection between the enhanced cascades is established by the inherent compensation that is provided by unique A-block in the local enhance cascade. A fundamental constraint within MECC(N,M) system design is thus:

$$M \geq 1 \Rightarrow N \geq 1 \quad (1)$$

MECC(N) provides optimized control in dedicated applications where filter linearity is unproblematic and the load is known. The MECC(N,M) provides optimized control in all general applications. Both topologies have their place.

2.1 Loop prototype based MECC(N) synthesis

In the following, general N-loop MECC(N) controller synthesis is addressed, with the proposal of a general recursive design procedure. The foundation is a *loop prototype* based design approach. Prototype based design leads to a highly regular and flexible structure where the resulting performance is easily evaluated independent of the number of loops in the system. Consider the simple MECC(N) loop prototype specified:

$$L(s) = \frac{\tau_{l1}}{\tau_{uN}} \frac{1}{\tau_{l1} s + 1} \tag{2}$$

The bandwidth of the loop prototype is determined by τ_{uN}. The MECC(N) topology itself does not inherently provide an improved control of the PMA system, as the comparison with the topologically similar NDFL method clearly illustrated. A crucial aspect is the implementation of the loop prototype is the forward and feedback path compensators. The prototype is realized with the following A-compensator block characteristic:

$$A(s) = \frac{1}{K} \frac{1}{\tau_1 s + 1} \tag{3}$$

Where K determines the resulting closed loop gain within the target bandwidth of the system. The advantages of this A-block characteristic is the filtering of HF-noise from the v_p-generator in the case that carrier based modulation is used. Furthermore, the characteristic effectively prepares the local enhanced cascade for the application of a further global enhanced cascade by implementing a closed loop compensation effect. With $A(s)$ determined the following initial compensator B_1 will realize the desired loop prototype:

$$B_1(s) = \frac{K}{K_{PN}} \frac{\tau_{l1}}{\tau_1} \frac{\tau_1 s + 1}{\tau_{l1} s + 1} \tag{4}$$

K_{PN} is the nominal gain of the power conversion stage. Its axiomatic that the realization of $L(s)$ in each loop, combined with the unique feedback path compensator $A(s)$ results in a system transfer function that is independent on N, i.e. a closed loop prototype for the local enhanced cascade:

$$H_N(s) = K\frac{L(s)}{1+L(s)} \approx K\frac{\tau_1 s+1}{\tau_{uN}s+1} \tag{5}$$

The realization of $L(s)$ in all succeeding loops requires the following compensator characteristic:

$$B_i(s) = \frac{\tau_{i1}}{\tau_{uN}}\frac{\tau_{uN}s+1}{\tau_{i1}s+1} \tag{6}$$

With the loop prototype based approach, MECC(N) optimization only requires optimization of a few fundamental parameters, independent upon the number of loops N. Furthermore, each compensator is simple and straightforward to implement. Both issues are pleasant features. Alternative loop prototypes are of second order [12].

2.2 MECC(N) properties

The analysis of MECC(N) now proceeds with a more fundamental investigation of the system properties, based on the loop prototype and compensator characteristics. General expressions are derived for the effective sensitivity function and the resulting closed loop transfer function. We have from Fig. 2:

$$v_p = K_{PN}B_1(B_2(B_3(\cdots B_N(v_r - Av_p)\cdots - Av_p) - Av_p) - Av_p) \tag{7}$$

This leads to the closed loop expression:

$$H_N = \frac{K_{PN}\prod_{i=1}^{N}B_i}{1+K_{PN}A\left[\prod_{i=1}^{N}B_i + \prod_{i=1}^{N-1}B_i + \prod_{i=1}^{N-2}B_i + \cdots + B_2B_1 + B_1\right]} \tag{8}$$

Which reduces to:

$$H_N = \frac{K_{PN}\prod_{i=1}^{N}B_i}{1+K_{PN}A\sum_{j=0}^{N-1}\left[\prod_{i=1}^{N-j}B_i\right]} \tag{9}$$

The significant importance of (9) becomes evident when investigating the effective system that is implemented by the MECC(N) topology. The *effective* *loop transfer function* L_N and – equivalently – the *effective sensitivity function* S_N are defined as:

$$L_N = K_{PN} A \sum_{j=0}^{N-1} \left[\prod_{i=1}^{N-j} B_i \right] \tag{10}$$

$$S_N = \frac{1}{1 + K_{PN} A \sum_{j=0}^{N-1} \left[\prod_{i=1}^{N-j} B_i \right]} \tag{11}$$

Every loop in the MECC(N) topology considered individually exhibits excellent stability, so adding or removing (identical) compensator blocks does not influence stability. Another important aspect is the *successive* improvement afforded by the enhanced cascade configuration as opposed to a higher order single loop approach.

Control signal characteristics

Another important aspect is the control signal level throughout the system, in terms of the response of the individual compensator blocks to the reference input. The control signal transfer functions are easily derived:

$$H_{Bi,N} = \frac{v_{bi}}{v_r} = \frac{v_p}{v_r} \left(\frac{v_p}{v_{bi}} \right)^{-1} = \frac{H_N}{H_i} \approx 1 \tag{12}$$

$$H_{A,N} = \frac{v_a}{v_r} \approx 1 \tag{13}$$

The "balanced" control signals are another advantage gained by the loop prototype based design. Systems with non-balanced control signal may be limited by the compensator performance.

2.3 MECC(N) loop shaping

In general, the process of MECC system design covers the same fundamental steps as for other linear control systems. The actual parameter optimization involving the specification of loop prototype and selection of the fundamental parameters is addressed in the following. Table 1 proposes a general set of parameters that serve as guideline to optimized MECC(N) design. It should be emphasized that the parameters are optimized for the MECC(N) topology specifically, i.e. the parameters change if the system is extended to MECC(N,M). The fundamental parameter τ_{i1} is chosen to realize the desired characteristic of the loop prototype.

Parameter	Value	Comment
$f_1 = \frac{1}{2\pi\tau_{p1}}$	f_o	A-block parameter
$f_{t1} = \frac{1}{2\pi\tau_{t1}}$	$\frac{1}{10} f_{uN}$	Pole frequency for loop prototype $L(s)$
N	$N \le 4$	Limit on necessary (and practical) number of loops in the MECC(N) structure.
f_o	2	Demodulation filter natural frequency
Q_{oN}	$\frac{1}{\sqrt{3}}$	Demodulation filter Q (Bessel)

Table 1 Proposed general MECC(N) parameter values.

A case example system is considered for the full audio bandwidth with a desired system gain of $K = 26dB$. The equivalent nominal power stage gain is assumed $K_{PN} = 26dB$. A parametric analysis of the achievable performance vs. N is carried out. The prototype bandwidth is selected to $f_{uN} = 5$. The proposed parameters in Table 1 are used, and all sub-controllers in the MECC(N) structure are now defined. Fig. 4 shows the components of first loop and the realization of the loop prototype $L(s)$. Following loops in the enhanced cascade are realized by the addition of further B_i blocks as shown in Fig. 4 and Fig. 5. Fig. 6 and Fig. 7 illustrates the effective loop transfer function L_N and sensitivity function S_N with the specified parameters. The Nth order transition caused by N poles and N-1 zeros in effective loop transfer is pronounced from the parametric analysis. The parametric investigation of the effective sensitivity function S_N verifies the excellent stability characteristics for the MECC(N) topology:

$$\|S_N\|_\infty < 1 \quad \forall \omega, N \tag{14}$$

This is a general property of MECC(N) with the proposed parameter values. The system response is shown in Fig. 8. The response is dominated by the post filter. With the specified parameters, the resulting system frequency response is acceptable in the nominal load.

Robustness properties

With the given first order prototype based design there is no theoretical limit to the number of loops that can be implemented in the MECC(N) structure. In practice however, there will be restrictions on the number of loops in the local enhanced cascade arising from uncertainty on e.g. the power stage gain K_{PN} and the modulator / power stage propagation delay t_p [12]. The effects on perturbations on K_{PN} and t_p can be isolated in the set of perturbed loop transfer functions:

$$L_{N,p}(r_K,t_p) = r_K K_{PN} A \sum_{j=0}^{N-1}\left[\prod_{i=1}^{N-j} B_{i,p}\right] \cdot e^{-t_p s} \\ = r_K e^{-t_p s} L_N \tag{15}$$

As shown in [12], the MECC(N) system is a very robust higher order control system. Additional uncertainty arises from the compensator itself. The compensator poles will affect the target band performance but only marginally influence the stability characteristics that are determined by the characteristics well beyond the target frequency band. Investigations have shown that even 10% tolerance on the compensator zeros will only marginally influence stability and performance.

3. The MECC(N,M) topology

The focus now turns to the extended topology with N local and M global loop formed in two linked enhanced cascades, shown in Fig. 3. The topology is founded on a MECC(N) design and should be seen as a direct extension of this topology. The MECC(N,M) topology is characterized by:

- A MECC(N) system, that is optimized specifically for the global enhanced cascade.
- A *single* feedback source v_o.
- A *single* feedback path compensator C.
- An D_1 compensator to initialize the cascade.
- A *recursive* structure with a set of preferably *identical* compensator blocks D_i.

The topological resemblance between MECC(N) and MECC(N,M) also leads to similarities in the synthesis of the two cascade structures. However, MECC(N,M) is constituted of two closely connected enhanced cascades, where the global enhanced cascade relies on the compensation from the local cascade. The following section will address the essential aspects MECC(N,M) design.

3.1 Loop prototype based MECC(N,M) synthesis

The control plant for the global enhance cascade is the MECC(N) controlled system $H_N(s)$ in series with the demodulation filter $F(s)$, which is assumed to have a standard second order characteristic:

$$H_N(s) \cong K \frac{\tau_1 s + 1}{\tau_{uN} s + 1} \tag{16}$$

$$F(s) = \frac{\omega_o^2}{s^2 + \frac{\omega_o}{Q_{oN}} s + \omega_o^2} \tag{17}$$

MECC(N,M) synthesis will be based on the specification of a unique loop prototype consistent with the approach for MECC(N) synthesis. A desirable loop prototype is again a leaky integrator characteristic:

$$L(s) = \frac{\tau_{i2}}{\tau_{uM}} \frac{1}{\tau_{i2}s + 1} \tag{18}$$

Clearly, the unity gain frequency (bandwidth) of the loop prototype is determined by τ_{uM}. The requirement for a system gain K locks the compensator characteristic of the feedback path:

$$C(s) = \frac{1}{K} \tag{19}$$

A connection between the local system and the global system is established by the following parameter assignments:

$$\tau_1 = \frac{1}{\omega_0} \quad \text{and} \quad f_{uN} > f_{uM} \tag{20}$$

This specific parameter assignment causes $H_N(s)F(s)$ to have a first order characteristic within the bandwidth of the of the local loop prototype for MECC(N). The initial compensator D_l that will realize the global loop prototype can now be specified:

$$D_1(s) = \frac{\tau_{i2}}{\tau_{uM}} \frac{\tau_1 s + 1}{\tau_{i2}s + 1} \tag{21}$$

Assuming that $f_{uN} >> f_{uM}$, the general MECC(N,M) system response will be:

$$H_{N,M}(s) \approx K \frac{1}{\tau_{uM}s + 1} \tag{22}$$

$H_{N,M}$ should be considered as a closed loop prototype that is synthesized *independent* upon M. This is axiomatic with a unique loop prototype and a unique feedback path. The general D_i- compensator that will realize the loop prototype in any succeeding loops is:

$$D_i(s) = \frac{\tau_{i2}}{\tau_{uM}} \frac{\tau_{uM}s + 1}{\tau_{i2}s + 1} \tag{23}$$

3.2 MECC(N,M) properties

Since the structure of both the local and global enhanced cascade is the same, many of the pleasant properties for MECC(N) can be generalized to MECC(N,M) directly. Fig. 3 yields the following relation:

$$v_o = H_N F D_1 (D_2 (D_3 (\cdots D_M (v_r - C v_o) \cdots - C v_o) - C v_o) - C v_o) \tag{24}$$

Or equivalently:

$$H_{N,M} = \frac{H_N F \prod_{i=1}^{M} D_i}{1 + H_N C F \sum_{j=0}^{M-1} \left[\prod_{i=1}^{M-j} D_i \right]} \tag{25}$$

The (N,M)-subscript in $H_{N,M}$ refers to that the M-loop MECC(N,M) design is based on the general N-loop MECC(N) system. The effective loop transfer function $L_{N,M}$ and the effective sensitivity function $S_{N,M}$ for the MECC(N,M) system are:

$$L_{N,M} = H_N C F \sum_{j=0}^{M-1} \left[\prod_{i=1}^{M-j} D_i \right] \tag{26}$$

$$S_{N,M} = \frac{1}{1 + H_N C \sum_{j=0}^{M-1} \left[\prod_{i=1}^{M-j} D_i \right]} \tag{27}$$

Looking at the resulting sensitivity function that specifies the reduced sensitivity to any errors within the fundamental elements of the PMA it is straightforward to show that the resulting sensitivity function is simply $S = S_N \cdot S_{N,M}$.

3.3 MECC(N,M) loop shaping

Table 2 proposes a set of parameters for generalized MECC(N,M) loop shaping. Again, is has been attempted to minimize the degrees of freedom without compromising performance. The free parameters with the general parameter assignment in Table 2 are N, M and the bandwidths of the local global prototypes f_{uN} and f_{uM}. It should be emphasized that the local (MECC(N)) should be optimized specifically towards the application of the global enhanced cascade. The local system should be optimized to provide best possible compensation, i.e. the bandwidth of the local system should be as high as possible. Only one local loop is necessary to provide the compensation. A

Parameter	Value	Comment
$f_{t1} = \frac{1}{2\pi\tau_{t1}}$	f_o	MECC(N) parameter
f_{uM}	$\leq \frac{f_{uN}}{2}$	MECC(M,N) bandwidth defined
$f_1 = \frac{1}{2\pi\tau_1}$	f_o	Connection between local and global enhanced cascade.
$f_{t2} = \frac{1}{2\pi\tau_{t2}}$	$\frac{f_{uM}}{10}$	MECC(N,M) loop prototype parameter.
f_o	1	Demodulation filter natural frequency
Q_o	$\frac{1}{\sqrt{3}}$	Demodulation filter Q (Bessel)

Table 2 Proposed general MECC(N,M) parameter assignments.

feasible approach is to implement a MECC(1) system with sufficient compensation effect, and following adjust M to the desired performance. The tradeoffs in MECC(N,M) design will become clearer throughout the more detailed investigation of an illustrative case example. The basic parameters are as for the MECC(N) case example. The prototype bandwidths of the specific case are set to $f_{uN} = 10$ and $f_{uM} = 4$ and M will be considered a variable parameter. N does not influence the global enhanced cascade and is set arbitrarily to 1. The bandwidth of the local MECC(N) system is inherently limited at $f_{uN} = 10$, and $S_{N,M}$ for the synthesized MECC(N,M) controller is shown in Fig. 9. The following is found by investigating $\|S_{N,M}\|_\infty$:

M	1	2	3	4
$\|S_{N,M}\|_\infty$	1.20	1.5	2.21	3.57

The system converges towards instability as the number of global loops increase due to the bandwidth limitation of the local system. Fig. 10 shows Bode-plots of all components of the MECC(N,M) system and Fig. 11 shows the system transfer function $H_{N,M}$ for $M = (1,2,3,4)$. Clearly, MECC(N,M) provides a much improved frequency response with the given parameters. Especially, the resulting response is excellent with both $M = 1$ and $M = 2$. The demodulation filter natural frequency is unity ($f_o = 1$), so the excellent frequency response characteristics do not compromise demodulation. It is beyond the scope of this paper to discuss robustness properties of the MECC(N,M) topology. Details on these aspects are given in [12].

4. Practical evaluation

The performance of MECC will be demonstrated by a simple MECC(1,1) realization of a 400W system for the full audio band. The system is based on a conventional 100V bridge power stage that has been tuned to maximize efficiency and to obtain clean transient free switching characteristics in the power stage. This leads to an open loop THD of 1-2% worst case. MECC is a general control method and works with a range of pulse modulation methods. The present system is implemented with a (patent pending) Controlled Oscillation Modulation (COM) approach [6]. The general parameters for the case example are defined below.

Parameter	Assignment
V_S	65V
K	26dB
Blanking delay	80ns
f_b	20KHz
f_c	400KHz
N	1
M	1

Fig. 12 shows illustrates the frequency response of the system in 2Ω / 4Ω / 8Ω / 16Ω. The system response is within ±0.3dB in all loads from 2Ω to an open load situation. This is due to the very low output impedance of the system, which is below 35mΩ at all frequencies.

Fig. 13 shows an FFT analysis of the amplifier output at 5KHz/100mW. The analysis reveals the extreme linearity of the MECC based PMA system at typical output powers. This is quite exceptional for such a high power PMA system and fully comparable with what is achieved by the very best linear power amplifiers. As shown in Fig. 14, a high level of linearity is maintained at all frequencies and output powers. Thus, THD+N maintains to be below 0.04% even at extreme output levels in the tweeter range. The specifications for the MECC(1,1) based PMA system are summarized below:

Max. cont. output power (8Ω/4Ω)	200W/400W
Bandwidth (3 dB)	80KHz
Frequency response (2-16Ω)	±0.2dB
Output impedance @ 20Hz-20KHz	<35mΩ
THD @ 1W/1KHz	< -100dB (0.001%)
THD+N (complete op. range)	<0.04%
Intermodulation Distortion (IMD)	< 0.01%
Residual noise (20Hz-20KHz)	50μV RMS (A)
Maximal efficiency	93%
Power loss at quiescence – Total	1.5W

Essential specifications MECC/COM based full bandwidth PMA system.

A picture of the ultra compact MECC/COM prototype is shown in Fig. 15. The practical evaluation of the MECC controlled PMA system has verified that the topology provides powerful control of all system parameters. The theoretical benefits are well implemented in practice.

5. Conclusions

The paper has adressed the issue of optimal control for analog PMA systems. A novel topology - Multivariable Enhanced Cascade Control (MECC) – has been introduced. Two variants were introduced MECC(N) and MECC(N,M). The concept of loop prototype based design was introduced to minimize the degrees of freedom within the higher order control structure. The functionality of both MECC(N) and MECC(N,M) approaches has been verified by synthesizing and evaluating illustrative case examples. 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. MECC(N) has shown to exhibit several pleasant properties:

- Powerful and flexible control of the power stage is realized.
- Pleasing signal levels throughout the control structure.
- Simplicity in implementation.
- Excellent robustness to any uncertainties with the power conversion stage.
- Effective compensation of the demodulation filter, thus preparing the system for a global enhanced cascade.

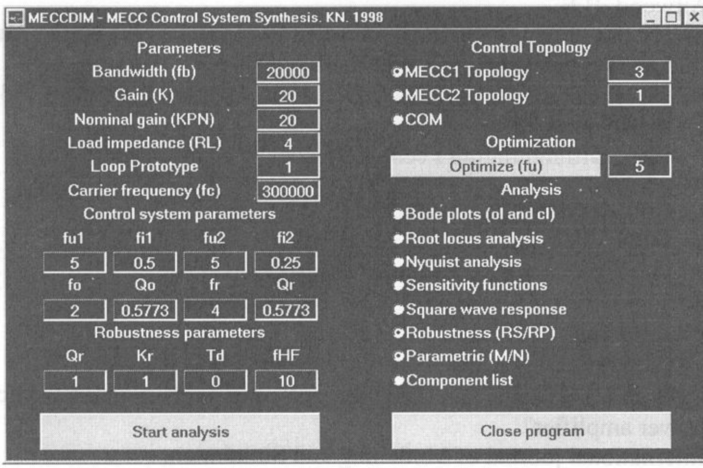
MECC(N,M) encloses the PMA by two closely connected enhanced cascades. The additional properties of the MECC(N,M) are improved frequency response insensitive to variable loading, and the compensation of any errors introduced within the filter. The practical evaluation of a simple MECC/COM PMA system has shown that simple configurations as MECC(1,1), MECC(1,2) or MECC(1,2) can provide excellent audio performance for even very non-linear and noisy modulator/output stage configurations. MECC is concluded to be the most powerful and flexible control method existing for general analog PMA systems. The presented amplifier specifications are believed to be state-of-the-art within the field.

6. Patent Note

The MECC topologies and design methods are protected by a pending patent (PCT/DK97/00497) [6]. For further information please contact Bang & Olufsen A/S, Denmark (the author).

7. Appendix

A GUI controlled MATLAB toolbox – MECCDIM – has been developed for systematic and automated design of MECC based PMAs. The graphical user interface is shown below.



The toolbox provides automated design by simple push button access. Based on the primary amplifier input parameter specifications the interface gives access to:

- Optimal control system synthesis and verifications
- Parametric analysis (vs. M and N).
- Robustness investigations.
- Controller component synthesis for low-level non-linear simulation.
- Manual access to individual parameters for fine-tuning of performance to e.g. a specific applications.

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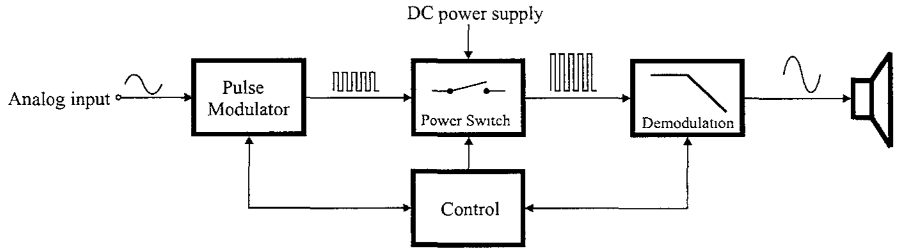

Fig. 1 General analog Pulse Modulation Amplifier topology.

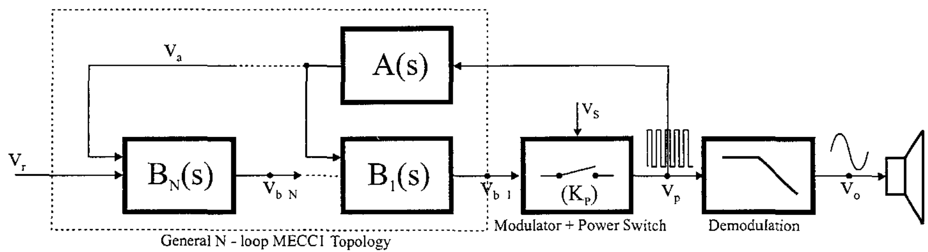

Fig. 2 General N-loop MECC(N) topology

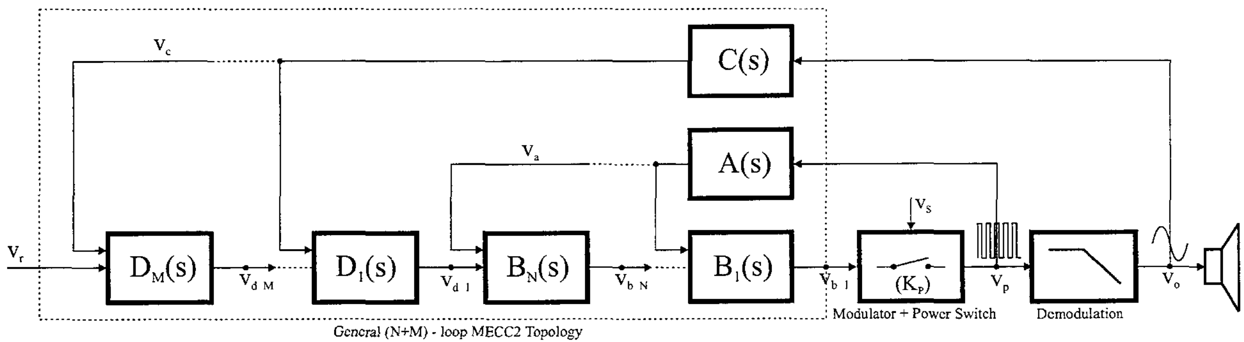

Fig. 3 General (N+M) - loop MECC(N,M) topology

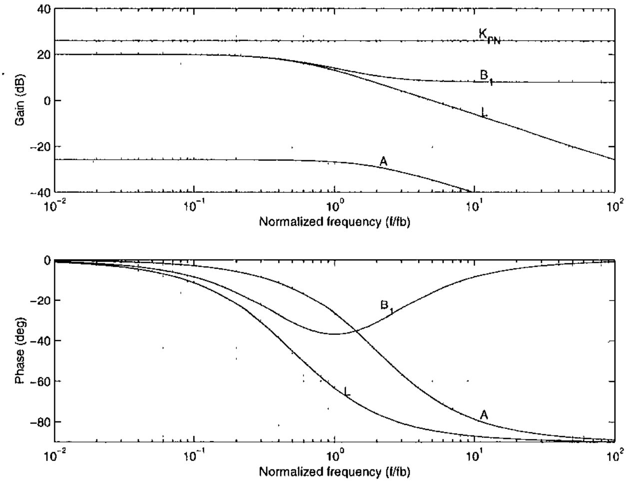

Fig. 4. Components of the first loop and the resulting loop prototype $L(s)$.

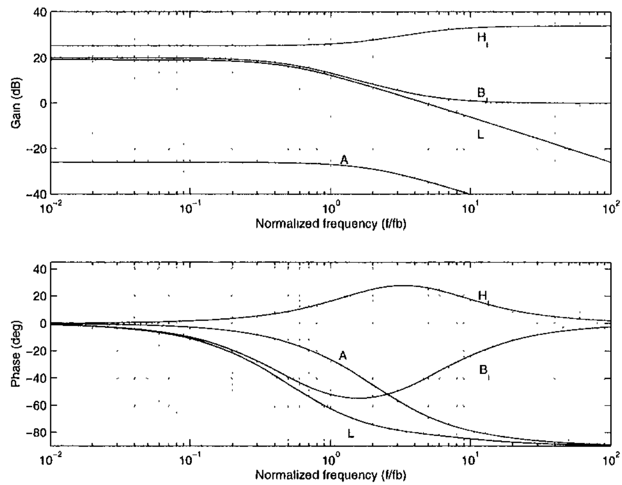

Fig. 5 MECC(N) case example. Components of any successive loop.

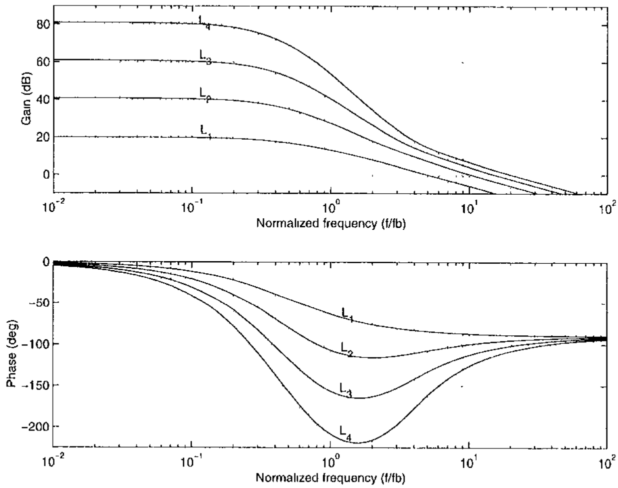

Fig. 6 MECC(N) parametric analysis of effective loop transfer function L_N . ($N = 1,2,3,4$).

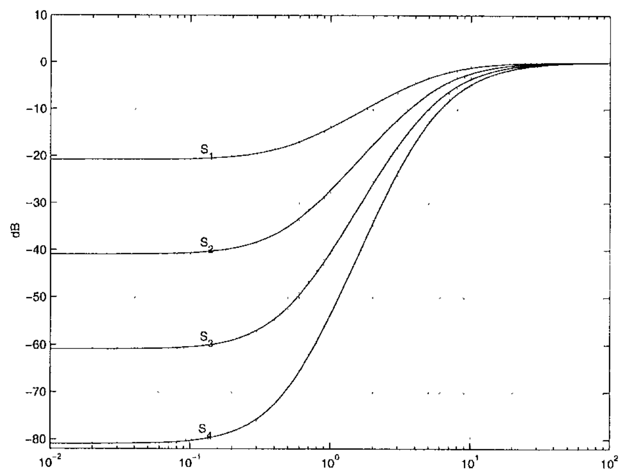

Fig. 7 MECC(N) parametric analysis of effective sensitivity function S_N . ($N = 1,2,3,4$).

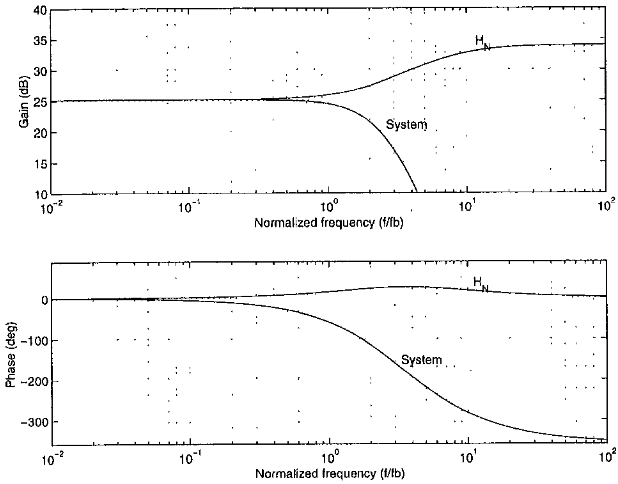

Fig. 8 MECC(N) case example system transfer function (independent of N).

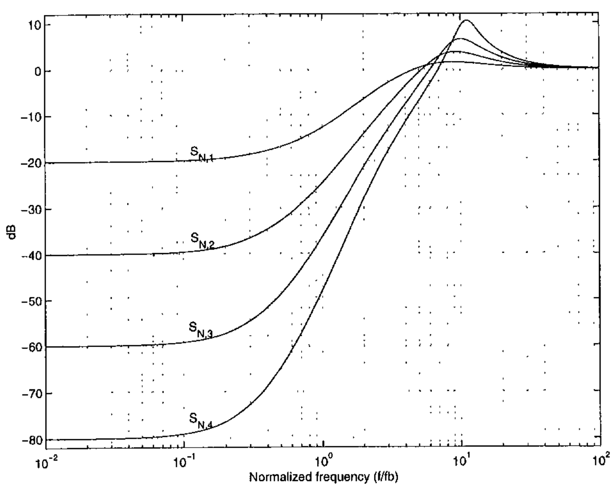

Fig. 9 $S_{N,M}$ for synthesized MECC(N,M) system $M = 1,2,3,4$.

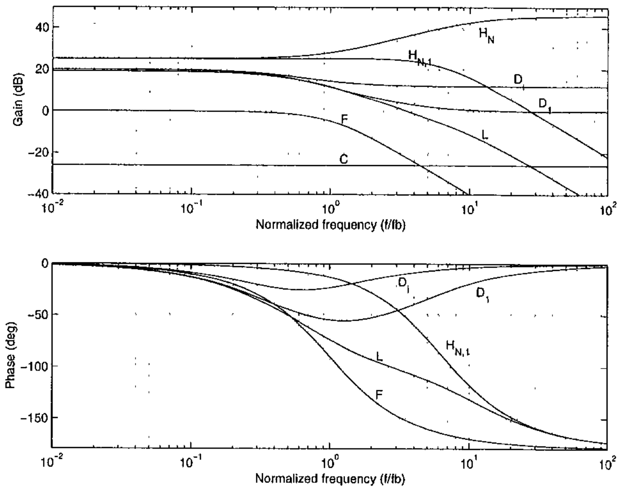

Fig. 10 Components of the MECC(N,M) system.

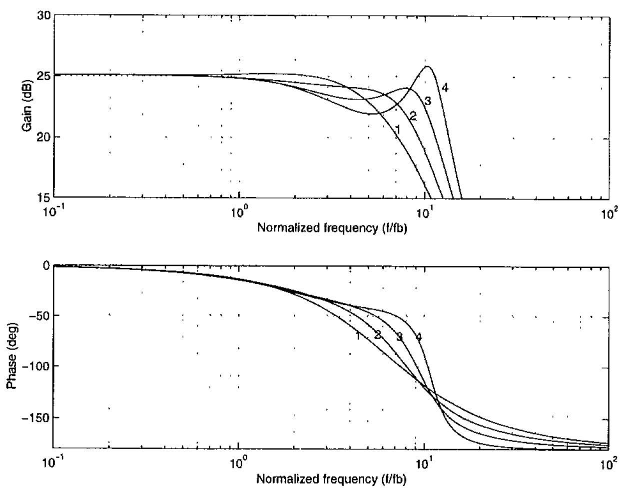

Fig. 11 Resulting system transfer function $H_{N,M}$, $M = 1,2,3,4$.

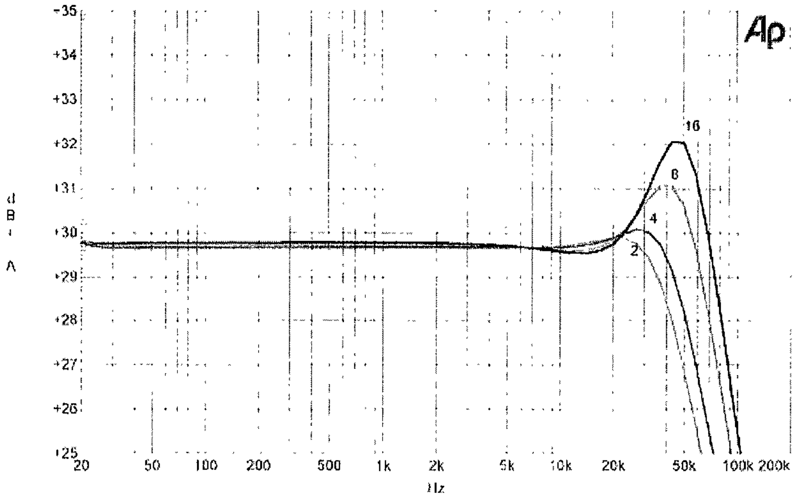

Fig. 12 Frequency response of the system in 2Ω / 4Ω / 8Ω / 16Ω.

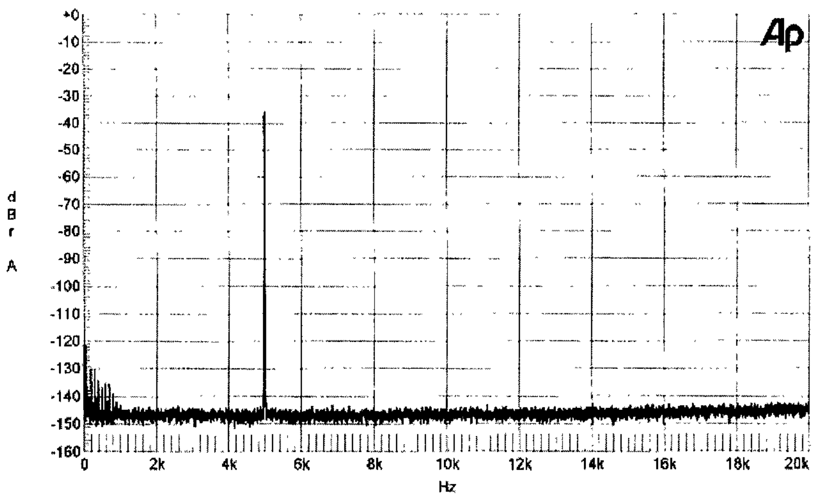

Fig. 13 FFT analysis of the amplifier output at 5KHz (100mW). THD=-106dB (0.0005%).

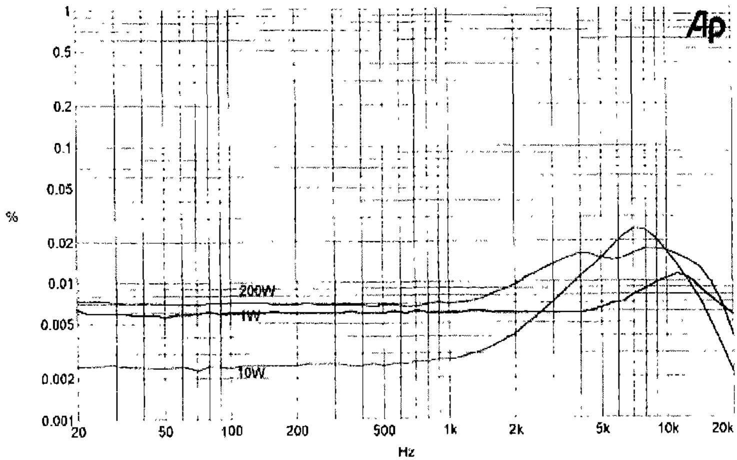

Fig. 14 THD+N vs. frequency at 1W, 10W and 200W (8Ω)

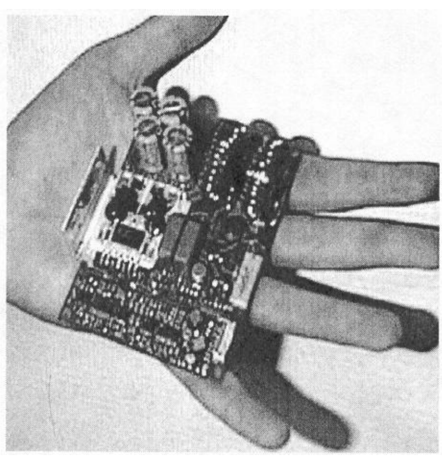

Fig. 15 Picture of the high end 400W(4Ω) MECC/COM based power amplifier module.