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Integrating switch mode audio power amplifiers and electro dynamic loudspeakers for a higher power efficiency

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Abstract— The work presented in this paper is related to integration of switch mode audio amplifiers and electro dynamic loudspeakers, using the speaker's voice coil as output filter, and the magnetic structure as heatsink for the amplifier.

I. INTRODUCTION

During the last few years switch mode audio power amplifiers (class-D) are introduced in still more audio products due to reduced cost, size and power efficiency compared to linear power amplifiers. As the case with switch mode power supplies, audio amplifiers can take benefit of the compactness caused by efficiency, which means a reduction in need for bulky heat sinks.

With a still higher demand for multi channel audio products, switch mode amplifiers are essential for the still more popular modern multi channel surround sound amplifiers and receivers.

Most commercial switch mode audio power amplifiers on market are having an output filter to attenuate the high frequency content of the amplified PWM signal from the power stage before reaching the output terminals of the amplifier. Only amplifier solutions for low power amplifiers [1] are made without output filter, but with restrictions for maximum cable length between amplifier and loudspeaker due to EMC.

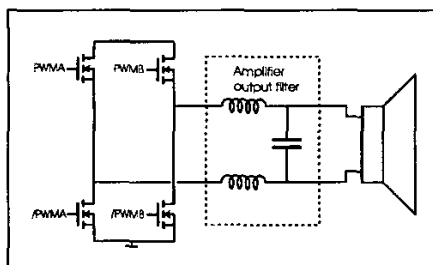


Figure 1 Combination of switch mode audio power amplifier and loudspeaker

By integrating switch mode audio power amplifiers and electro dynamic speakers into one single unit several advantages can be achieved:

- By using the inductive behavior of the speaker's voice coil as output filter, the expensive parts for an output filter for the amplifier could be omitted
- By dedicating amplifier and loudspeaker, the standard interface between is broken down, giving a new degree of freedom of choosing amplifier voltages and currents and speaker impedance
- Mechanical and thermal integration neglect the need for additional cooling of the amplifier, and cost will be reduced
- Power efficiency from electrical input to acoustic output can be significantly increased
- Additional features such as motional feedback of the speaker's diaphragm to linearize the acoustic output could easily be implemented

In practical use, the amplifier and speaker is used primarily at low output levels. The ratio between maximum peak values of music or speech and the average level, the crest factor, is very high, and furthermore the average level of listening is background or lower level listening [2]. From this it can easily be seen that improving overall system efficiency for practical usage first of all means reducing losses at idle and at low output levels.

II. SPEAKER MOTOR SYSTEM

The motor system of an electro dynamic loudspeaker is basically a coil, the voice coil, placed in a magnetic field, the air gap of the magnetic system. The magnetic system consists of a permanent toroid magnet with some iron parts to direct the magnetic field to the air gap. The bottom of the magnet is connected to a bottom plate, in which center a pole piece is placed to guide the magnetic field lines to the air gap. On top of the magnet a top plate with a circular hole is placed. The cross section of the pole piece is T-shaped with top dimensions corresponding to the thickness of the top plate, so a fairly uniform field distribution is obtained within the air gap.

A simplified drawing of the motor system the loudspeaker, is shown in Figure 2.

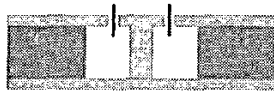


Figure 2 Magnetic system of electro dynamic loudspeaker, the dark areas is the permanent magnet, the gray areas the iron parts of the system, and the black areas is the voice coil placed in the air gap of the magnetic system.

Efficiency of the speaker is directly proportional to the Bl -factor, which is the effective B -field in the air gap multiplied with the length of the winding of the voice coil placed in the field. To achieve high efficiency it is necessary to hold a strong B -field, which the parts of the magnetic system surrounding the air gap of cause should hold.

Further more the volume of the air gap should be kept to an absolute minimum to ensure a strong B -field with a given permanent magnet. The materials of the magnetic system parts surrounding the air gap are usual iron due to magnetic capabilities and especially cost.

The force applied to the diaphragm of the speaker is given by $F = Bl \cdot I$, where I is the voice coil current. Hereby the efficiency of the motor system will be directly proportional to $\frac{Bl}{\sqrt{R_{DC}}}$ where R_{DC} is the DC resistance of the voice coil.

III. ELECTRO DYNAMIC SPEAKERS AS LOAD

Ideally the electrical system of a loudspeaker can be reduced to an inductor with a series resistor, when looking at frequencies beyond the mechanical and acoustic resonances of the system, hence the high frequency impedance should nearly be pure imaginary with a phase shift of close to 90 degrees. Unfortunately the case with the loudspeaker's high frequency impedance, the voice coil impedance, is similar to any other inductors, where several parasites influence the behavior. The major deviation from the ideal inductor is eddy current losses in the magnet system's parts surrounding the voice coil

[5], which adds to the real part of the high frequency impedance, degrading the phase shift. Furthermore stray capacitances causes the impedance to have a highly resonant behavior at high frequencies.

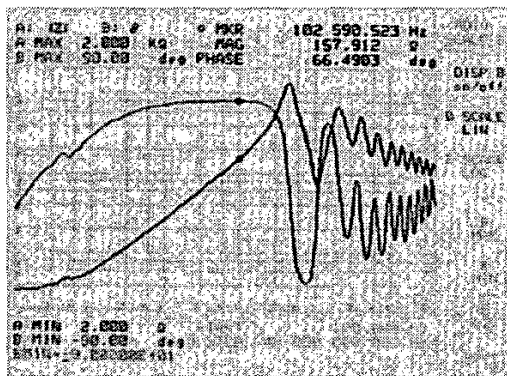


Figure 3 Impedance measurement of a 10" woofer

Figure 3 shows the electrical impedance of a 10" woofer used for initial tests. The voice coil is a 2-layer winding on a non-conducting coil former made of fiberglass. The phase shift of the voice coil inductance has a maximum of only 67 degrees what strongly indicates the eddy current problem in the magnetic system

[5]. At approximately 500 kHz a peak of the impedance occurs followed by a series of resonances, caused by stray capacitances in the magnetic system.

The stray capacitances are the sum of turn-to-turn, layer-to-layer and coil-to-surroundings capacitances, where the layer-to-layer capacitance is the far most dominating. The-layer-to-layer capacitance is given by [4]:

$$C_{ll}(p) = \frac{4C_{ll}(p-1)}{3p^2}$$

Where C_{ll} is the capacitance between two winding layers, and p the number of layers. It can easily be seen that the total capacitance can be significantly reduced if the number of winding layers is increased, but unfortunately this will decrease overall efficiency due to increased volume of the air gap in the magnetic system, which will reduce the B -field and thereby reduce the ratio $\frac{Bl}{\sqrt{R_{DC}}}$ of the coil.

IV. OUTPUT OF AMPLIFIER

Since the amplifier is connected directly to the loudspeaker without any output filter in between, the output signal from the amplifier will be the amplified PWM signal.

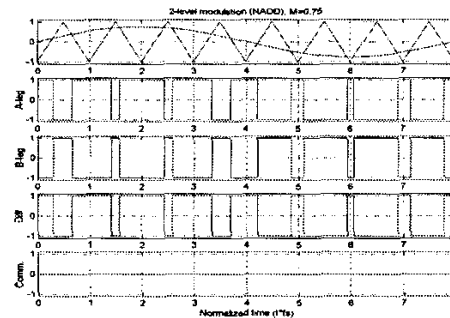


Figure 4 2-level PWM signals

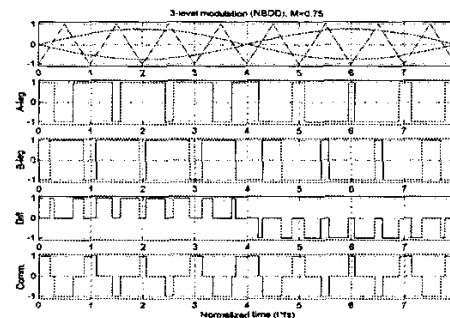


Figure 5 3-level PWM signals

The high frequency content of the PWM signal is, of course strongly dependent on the modulation scheme used. The lowest high frequency content will be for double sided, natural sampling, which means that the carrier signal is a triangular signal instead of the often used saw tooth waveform [2].

All amplifiers used are full audio bandwidth amplifiers and have a full-bridge power stage, which gives the amplitude of the PWM output +/- the power stage supply voltage.

Figure 4 and Figure 5 shows generated PWM signals for 2- and 3-level modulation, where M is the modulation index, the ratio between actual and maximum output level. It is clearly seen, that the 3-level modulated output signal holds a common mode signal dependant on the reference signal.

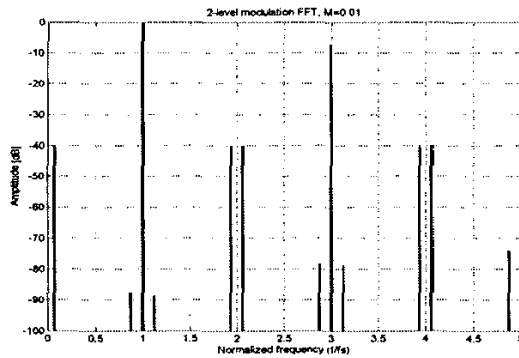


Figure 6 PWM FFT spectrum, 2-level, differential output, M=0.01

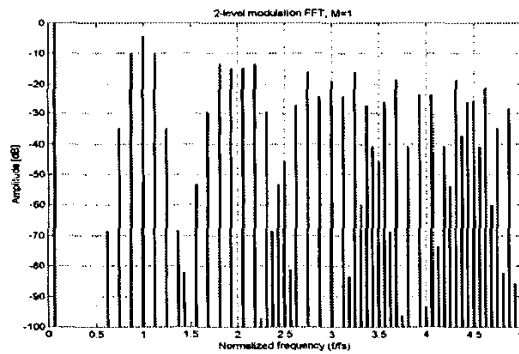


Figure 7 FFT spectrum, 2-level, differential output, M=1

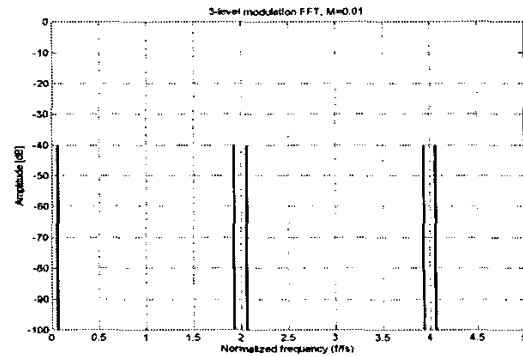


Figure 8 FFT spectrum, 3-level, differential output, M=0.01

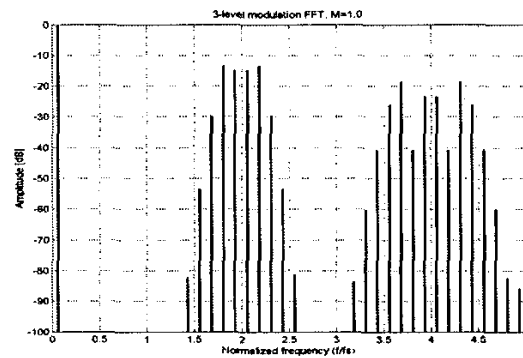


Figure 9 FFT spectrum, 3-level, differential output, M=1

Figure 6 to Figure 9 shows FFT spectrums of the 2- and 3-level modulated PWM signals for M= 1 (max) and M=0.01 reference voltage. It is clearly seen that the switching frequency, the odd harmonics and the sidebands modulated to these has disappeared in the 3-level case. This difference is exactly the same as the FFT spectrum of the 3-level common mode signal, which is not shown. It can also be seen that the effective switching frequency is doubled in the 3-level modulated case, which means that the amplifier could be operated at halved switching frequency compared to the 2-level modulated still achieving same performance.

V. CONNECTING AMPLIFIER AND SPEAKER

An initial test setup was build with a 10" woofer in a vented box and a modified ICE250A [3] amplifier module. The amplifier was modified by disconnecting the outer control loop working after the output filter as well as a relay was mounted across the output filter to bypass this. Furthermore the switching frequency was adjusted to 500kHz, where the first impedance peak of the loudspeaker's impedance occurs. It was not possible to prove any difference in audio quality whenever the output filter was in series with the speaker or bypassed, but

measurements of power consumption did show significant power losses in the speaker:

50V power stage supply voltage, 2-level modulation	With output filter	Without output filter
Idle losses, total	1,59W	4,45W
Power loss, speaker, calculated	≈0W	3.13W

TABLE 1 POWER LOSSES, 2-LEVEL SETUP

For the calculated power losses only the first 9 harmonics of the switching frequency were used, due to finite slopes of the PWM output signal from a real power stage, which lowers the high frequency content. As load impedance were used the complex impedance of the speaker shown in Figure 3. The core loss in the inductor in the output filter of the amplifier is 1W, which should be taken into account in the losses comparison (the amplifier power stage loss is 590mW with output filter).

The additional power loss is due to increased switching losses because the ripple current through the output filter inductor (here the voice coil with a low frequency induction of 1mH) is much reduced compared to the filter inductor in the amplifier's output filter (20µH), thus reducing soft switching of the power stage and thereby giving a harder switching.

Since the RMS value of the harmonics of the idle 50% duty-cycle PWM signal are $A(m) = \frac{4 \cdot \pi}{\sqrt{2} \cdot m}$, it will almost be

impossible to reduce power losses in the loudspeaker unless another modulation scheme such as 3-level modulation is used and/or if the output voltage from the amplifier can be significantly reduced.

VI. IMPROVING OVERALL SYSTEM EFFICIENCY

As stated above the overall system efficiency can be increased by 3-level modulation and lowering the power stage voltage. By lowering the voltage, the energy stored in the capacitances of the MOSFETs will be reduced by a factor of the square of the reduction (if the capacitance values are unaffected), which would lead to reduction of amplifier losses as well as losses in the loudspeaker. To prove this, a low impedance voice coil was made as well as a 3-level modulated amplifier with a power stage supply voltage of 5V.

3-level modulated amplifiers, idle losses	48V supply voltage 250kHz	5V supply voltage 280kHz
Idle losses, amplifier + speaker	2.6W	600mW
Idle losses, amplifier with open load	2.6W	600mW

TABLE 2 POWER LOSSES, 3-LEVEL SETUP

The amplifier was designed for 100W output power,

which gives 40A peak into a 125mΩ load. Because of the high currents at high output levels, the efficiency will be reduced here due to conducting losses, but with the very high crest factor in music, this is of much less importance than the idle and low output power losses.

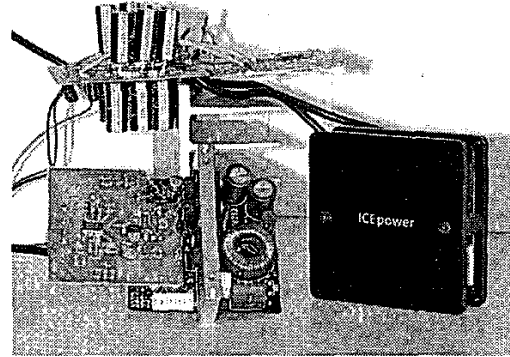


Figure 10 Std. and 3-level modified ICE250A module, 5V amplifier

The low voltage amplifier was compared with An ICE250A amplifier modified by using a 3-level modulator and removing the output filter. Since the 3-level modulation effectively doubles the switching frequency, the switching frequency of the amplifier was only 250kHz/280kHz (500kHz/560kHz effective) compared to the 500kHz in the 2-level setup.

The ideally zero output differential voltage for a 3-level modulated amplifier causes no differential output ripple current, thus removing soft switch capabilities of the output stage, increasing switching losses. Furthermore the common mode output of the amplifier will charge the voice coil-to-surroundings capacitances of the magnetic system, and these will appear in parallel to the capacitances of the MOSFETs, increasing switching losses further.

As seen in Table 2, the switching losses for the low voltage amplifier was reduced more than by a factor of 4 compared to the standard voltage amplifier even though the low voltage amplifier was an early prototype which easily could be optimized to lower losses.

VII. IMPROVING VOICE COIL EFFICIENCY BY A HIGHER FILL FACTOR

Efficiency of the motor system of the speaker, the combination of the magnetic system and the voice coil, can be improved. Since the power loss in the voice coil itself is directly proportional to the fill factor, the ratio between the conducting area and the total air gap volume, attempts to improve this should be considered.

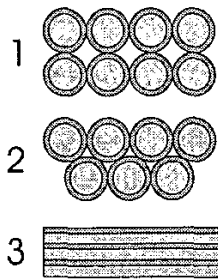


Figure 11 Voice coil winding layout

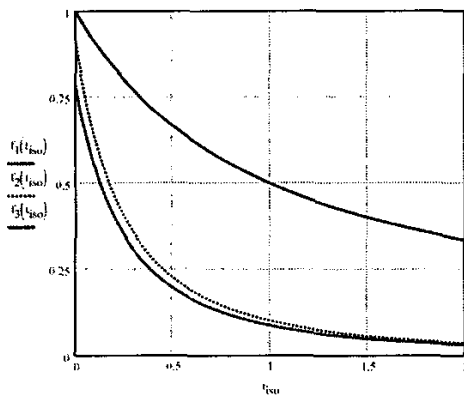


Figure 12 Voice coil winding fill factors

Figure 11 shows different voice coils fills. 1) and 2) is wire wound coils, where 2) is illustrating the typical winding layout of a voice coil. 3) shows a coil with a foil winding. Figure 12 shows the fill factors for the three winding layouts as a function of the ratio between the thickness of the conductors and the isolation. Figure 12 shows clearly that the highest fill factor is obtained with foil windings.

If the voice coil is made from a foil winding, two major factors should be taken into account, the electrical impedance and eddy current losses as a function of the voice coil movement [5]. Since the number of turns in a foil coil will be the same as the number of layers, and thereby restricted by the air-gap and foil thickness, a foil coil will have a small impedance.

Some important characteristics of using a foil winding:

- Low conducting losses for a certain $Bl \cdot i$ due to the high fill factor
- Low impedance due to low number of turns
- Low stray capacitance due to multiple layer-to-layer capacitances in series (first resonance on the impedance characteristic will be at a higher frequency)
- Possible eddy current problem [5]

The eddy current problem can be avoided by sliding the foil as shown in Figure 13, whereby the desired high fill factor can be obtained, and the resulting electrical impedance will rise due to higher number of turns and

smaller conductor area.



Figure 13 Sliding the foil winding

VIII. REDUCING LOSSES IN THE MAGNETIC SYSTEM

The impedance characteristics of a standard 10" woofer in Figure 3 shows large deviations from a pure inductive behavior below the resonances caused by a non-ideal behavior of the magnetic system. Since the complex electrical impedance has a real part caused by eddy current losses in the magnetic system, power will be dissipated in this real part when applying a signal.

To reduce eddy current losses in the magnetic system, a 3-level modulation scheme could be used to minimize the high frequency content of the applied signal as stated above, or the magnetic system itself could be modified to reduce the losses. A proper modification of the magnetic system would be a modification, which improves the inductive behavior of the lower frequency impedance, pushing the phase shift of the impedance closer to 90°. This could be done by changing the material of some or all of the iron parts of the magnetic system to a material with lower conductivity and magnetic losses, e.g. ferrite or iron powder materials.



Figure 14 Modified magnetic system 1



Figure 15 Modified magnetic system 2

Figure 14 and Figure 15 shows two ways of modifications to the standard magnetic system shown in Figure 2 to reduce eddy currents by using other materials in the parts close to the voice coil, such as ferrite or iron powder. The Dark areas are the parts of the system, which are changed. The difference between the two is the geometry of the top of the pole piece, and can be chosen or modified for the actual manufacturing procedure. Special attention should be paid to magnetic saturation if ferrite is used, since typical B_{max} is below 500mT. Iron powder could be the proper choice because of a B_{max} between 1 and 1.5T, dependant of the material grade. Furthermore machining iron powder is easier due to the relatively soft, non-ceramic material.

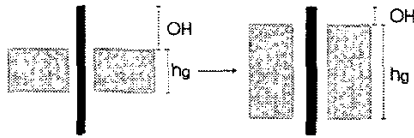


Figure 16 Effective use of voice coil

Using a material with a low B_{max} , such as ferrite, the air gap of the magnetic system should be higher in order to maintain a high number of magnetic field lines, so the applied force on the diaphragm of the speaker will be obtained. In Figure 16 an illustration of the requirements for the height of the air gap is shown for a standard and e.g. a ferrite based system. The “voice coil efficiency”, the relative use of the voice coil, can be defined as:

$$\eta_{vc} = \frac{h_L}{h_L + 2OH}$$

where OH is the overhang, which

ensures a certain linear motion of the voice coil, and h_g is the height of the air gap. If OH is kept constant, the voice coil efficiency will be improved by making the air gap higher, which would be required if ferrite was used. The trade offs of voice coil efficiency are the coil weight, total system weight and cost as well as manufacturing cost, both materials and tools.

B. Iron powder based prototype magnetic system

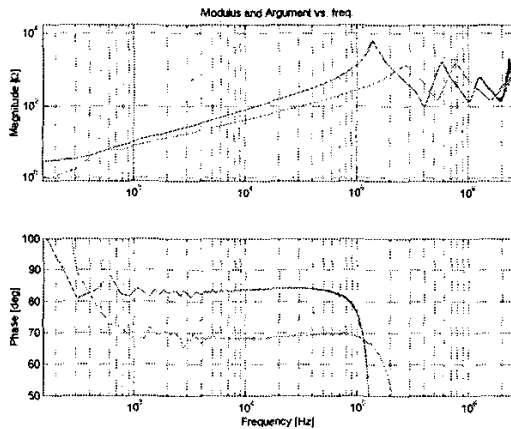


Figure 17 Impedance, Standard and prototype magnetic system, standard voice coil, light gray is the standard system, dark is the prototype system

A prototype magnetic system based on iron powder has been built as shown in Figure 14. The prototype system has the same physical dimensions as a standard system from a 10” woofer for direct comparison. The magnetic fields in the air gaps of the two systems are exactly the same.

Figure 17 shows the impedance characteristics of the standard and prototype magnetic systems with use of a standard wire wound voice coil. As seen, the magnitude of the impedance is higher in the prototype system, as well as the phase shift is significantly improved, due to large reduction of eddy currents.

Power losses for the standard and prototype magnetic systems are calculated and shown in Figure 18 to Figure 21, based on the Fourier series from above. The plots are power losses vs. switching frequency for both 2- and 3-level modulation, and different M.

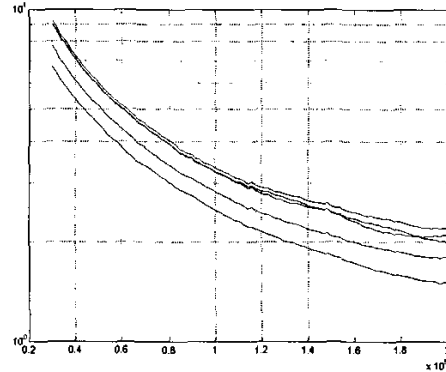


Figure 18 Power loss vs. switching frequency, standard magnetic system, 2-level modulation, M=0, 0.25, 0.5, 0.75, 1

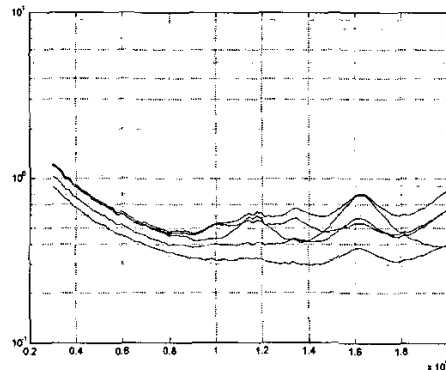


Figure 19 Power loss vs. switching frequency, prototype magnetic system, 2-level modulation, M=0, 0.25, 0.5, 0.75, 1

As seen in Figure 18 and Figure 19, the power losses are significantly lower with the prototype system when using 2-level modulation. At 100kHz switching frequency the difference is about an order of magnitude between the two systems.

As seen in Figure 20 and Figure 21, the power losses are lower with the prototype system when using 3-level modulation, but the difference between the two is no longer significant. Acceptable power losses are obtained with both systems.

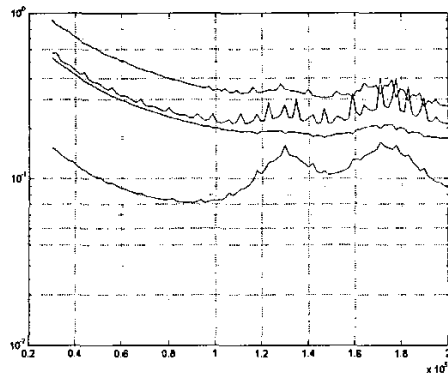


Figure 20 Power loss vs. switching frequency, standard magnetic system, 3-level modulation, $M=0.25, 0.5, 0.75, 1$

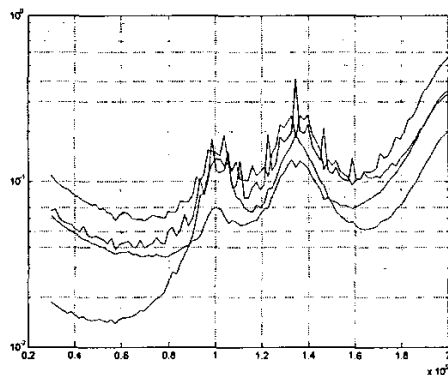


Figure 21 Power loss vs. switching frequency, prototype magnetic system, 3-level modulation, $M=0.25, 0.5, 0.75, 1$

IX. AUDIO QUALITY

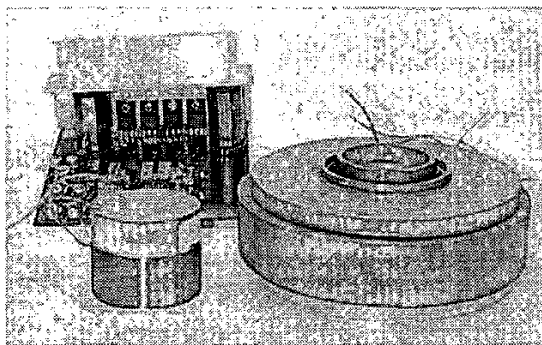


Figure 22 Voice coil, magnetic system and 2/3-level test amplifier

To investigate possible influence of different modulation schemes, a filterless test amplifier has been build. The amplifier has two modulators, a 2-level and a 3-level modulator, with a shared power stage. Change between the modulation schemes is obtained momentarily, and a direct comparison can be made. Listening test involving a selected panel of persons has been carried out. The output of the test

amplifier has been compared to a standard ICE250A amplifier containing an output filter. Figure 22 shows the test amplifier used in the listening test together with a magnetic system from the above mentioned 10" woofer and a voice coil. The listening tests have not proven any audible degradation in sound quality of the speaker when switching directly to the speaker terminals, using the speaker as output filter.

X. CONCLUSION

Increasing efficiency of the combination of an amplifier and loudspeaker will be possible through dedication and integration. Test results have proven that using low voice coil impedance combined with a 3-level modulated amplifier driven from a low voltage supply, power losses can be greatly reduced for practical use of the system. Other improvements would be use of e.g. iron powder materials in the magnetic system of the speaker. An iron powder based prototype magnetic system indicates great reductions in power loss in the magnetic system. With this prototype system the lowest losses are obtained with a 3-level modulation scheme, but losses are generally of a magnitude where a lower complexity 2-level modulation scheme can be used, still with satisfying results. Furthermore cost of the system can be reduced because the output filter of the amplifier can be omitted, and the speaker itself can be used as heat sink for the amplifier.

Listening tests has not proven any degradation in sound quality compared to a conventional switch mode amplifier with an output filter.

ACKNOWLEDGMENTS

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