Efficient Audio Systems

A modern audio reproduction system comprises of one input block, the input signal, and three hardware blocks, the power supply, the power amplifier and the loudspeaker. The system is meant to handle an infinite combination of sine waves within the audible range, 20 Hz to 20 kHz, with a dynamic range of up to 120 dB. Being able to do this with low Total Harmonic Distortion plus Noise (THD+N) is the requirement in modern audio reproduction systems. In recent years high efficiency and small size has become key parameters partly due to the fact that audio reproduction systems have evolved into battery driven portable devices. This has made switch-mode technology widely used in audio reproduction systems. However a consequence of shrinking the audio reproduction systems is reliability issues which always is a key parameter. It is with respect to these key parameters; efficiency, size and reliability, this thesis examines each block of the audio reproduction system identifying limitations and methods to overcome them. Sine waves are the common test signal when designing audio reproduction systems.

Sine waves have a crest factor of 3 dB and based on an analysis of 183 music tracks they are found to represent music poorly. The analysis shows that the average crest factor of music is 15 dB thus causing conventional designs to be improper, favouring sine wave operation. The impact on switch-mode power audio amplifier design from this understanding of the audio input is listed below:

- A new test signal is proposed based on amplitude distribution of real music. It is analytically described and has fundamental periodicity making it a serious replacement signal for conventional sine waves. With a crest factor of 14 dB it is very close to that of actual music which is found to be 15 dB and compared with sine waves that have a 3 dB crest factor the proposed signal is almost a factor seven more precise in modelling the dynamics.
- Experimental results on a conventionally designed 12 V switch-mode power audio amplifier demonstrate a 10 % point efficiency improvement when choosing switching devices based on the proposed signal instead of sine waves.
- A new switching strategy beneficial for power dissipation in switching devices is proposed. Experimental results on a 100 W test amplifier show a 45 ◦C reduction of operating temperature compared to conventional implementation.
- Measured results on a 150 W prototype amplifier using the proposed strategy show power density of 11.5 W/cm3. That is almost a factor three higher than recognized state-of-the-art amplifier modules. Moreover it is demonstrated that by using the proposed switching strategy size can be reduced more than a factor two compared to a conventional implementation.

The proposed switching strategy utilizes a high ripple current in the output filter inductance to improve soft switching capabilities when playing audio so that the power dissipation is moved away from the switching devices into the output filter which functions as a natural heat sink. The high ripple current affects the amplifier’s frequency response making classical control sub-optimal. An alternative method using full state control is proposed. Experimental results on a 1 MHz prototype amplifier show that frequency response ripples are effectively removed while delivering THD+N levels down to 0.01 %. Conventional power supplies for switch-mode audio power amplifiers supply the amplifier with a fixed voltage. An alternative approach employing envelope tracking known from RF amplifiers is proposed. Measured results on a 100 W prototype system, comprised of a multi-level power supply and a switch-mode audio power amplifier, show that efficiency is improved up to a factor of 6 when playing real audio signals. The temperature rise is strongly reduced, especially for the switching devices of the amplifier where it is halved from 100 ◦C to 50 ◦C effectively increasing reliability and life span due to less thermal stress. The total system efficiency is dominated by the loudspeaker efficiency, in the range 0.2 % to 2 %. To counter that:

- A new voice coil design method is proposed. Analysis shows that the relationship between voice coil fill factor and loudspeaker efficiency is proportional. Using rectangular winding layout may increase the fill factor. Experimental results show a 25 % efficiency improvement when increasing the fill factor from 45 % to 53 %.

Increasing fill factor using a rectangular winding layout will result in a lower nominal resistance of the loudspeaker. This has a positive effect on a system level as it allows the amplifier to deliver more power from the same supply level. Measured results show that by using a 1 Ω load resistance instead of a conventional 4 Ω the efficiency is improved 10 % point at 1 W output power. In systems normally needing a boost converter, like automotive and portable electronics, this improvement can even be greater as the the low load resistance eliminates the need for supply voltage boosting. Measured results demonstrate a 25 % point efficiency improvement at 1 W output power for such systems. The findings of this thesis show that a high continuous output power is not a key parameter for music applications. The new test signal is currently under investigation by a subcontractor to the EPA U.S Energy Star program for use in test methods for a standard. High peak power is still needed for reproducing the peaks in dynamic audio signals. This points towards that future challenges in audio reproduction system design are high supply voltage levels and better loudspeaker efficiencies. In that sense this thesis outlines methods to overcome these challenges.

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