Class-D Amplifiers
in an Undergraduate Power Electronics Course

Daniel W. Hart
Valparaiso University

Abstract

The class-D amplifier is a recent development in audio electronic engineering. Class-D amplification utilizes power transistors as switches, producing a pulse-width modulated signal that is filtered and delivered to a speaker. Compared with other designs such as class AB amplifiers, the class-D scheme is much more energy efficient and compact. Because the circuitry is similar to others in power electronics, the class-D amplifier was a natural addition to our undergraduate power-electronics course.

This paper describes the student-designed experiences and the hardware that students selected to implement class-D amplifiers. Included are results from the student projects based on Texas Instruments equipment, National Semiconductor components, and an original amplifier design.

Introduction

Power electronics has been a popular elective course in the Department of Electrical and Computer Engineering at Valparaiso University for several years. In power electronics, electronic devices are used as switches in circuits that convert one form of voltage or current to another. One example of a power electronics circuit is an inverter for converting DC to AC. Class-D amplifiers use the same switching theory as in pulse-width modulated (PWM) power inverters. One power-inverter switching scheme uses PWM, wherein a reference waveform (usually a sinusoidal) is compared to a triangular "carrier" waveform operating at a frequency much higher than the reference [1, 2]. In class-D amplifiers, the sinusoidal reference waveform is replaced with a low-power audio signal, and the filtered PWM output of the inverter becomes the amplified audio signal.

The energy-savings aspect of class-D amplification has long been known and has been well documented [3]. In class-D amplification, an audio signal is converted to a pulse-width modulated voltage that changes between two levels. Power losses are mainly due to imperfect switching in the transistors during voltage transitions. Most audio amplifiers use the well-known class AB amplification method. The maximum theoretical efficiency of class AB amplification is 78%, compared to 100% for class D. In practice, with real audio signals, class-AB efficiency is much lower. In one Texas Instruments test, a class-AB amplifier was 20% efficient, compared to 75% efficient for class D [3]. Class-D amplifiers are becoming more prevalent in consumer electronics applications were greater efficiency results in reduced size and increased battery life.

In the fall of 2003, a guest speaker from Texas Instruments explained and demonstrated class-D audio equipment to the power-electronics class. Seeing that students were

Proceedings of the 2005 American Society For Engineering Education Annual Conference & Exposition

inspired, I proposed an optional laboratory project on class-D amplifiers, and five students participated. The hardware that the students used to implement their class-D amplifier projects and student opinions about the experience are described below.

The Hardware

Class-D amplifiers contain a triangular-waveform generator for the high-frequency carrier signal, a comparator to compare the carrier signal with the audio signal, and power transistors arranged in an H-bridge to switch the output voltage to either a high or low voltage depending on the output of the comparator. A passive Butterworth filter on the output of the H-bridge allows the audio portion of the PWM signal to be delivered to the speakers. The systems investigated by the students were (1) a self-contained class-D integrated circuit from Texas Instruments, (2) a two-IC system from National Semiconductor, and (3) a student-designed system constructed from basic components.

Students started their investigation into class-D amplifiers with evaluation boards provided by Texas Instruments. The evaluation boards contained the TPA005D02 component, which was designed for use in notebook PCs [4]. The TPA005D02 contains all the components (triangular waveform generator, comparator, H-bridge, and filter) for class-D amplification.

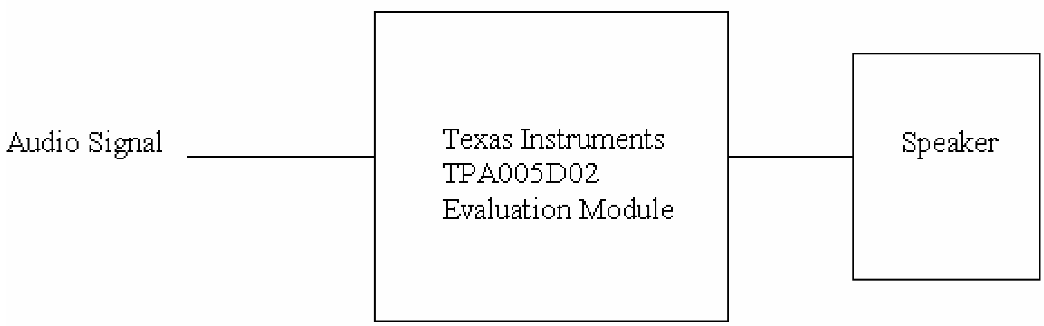

Figure 1. Block diagram of the simplest system using the Texas Instruments TPA005D02 class-D amplifier. The system is self-contained in the TI evaluation module.

After successfully investigating the operation of the Texas Instruments equipment, the students concluded that they would like to gain more insight into the class-D process. Consequently, they decided to build class-D amplifiers from more basic components.

The second system investigated was the National Instruments two-IC combination of the LM4651 driver and LM4652 power MOSFET array. This combination is intended for use as a class-D subwoofer amplifier [5]. The LM4651 contains an oscillator, PWM comparator, and MOSFET high- and low-side drivers. The LM4652 contains two pairs of MOSFETs for operation as an H-bridge. With this system, the students had to assemble the circuit on a breadboard and were required to select several external resistors, capacitors, and inductors. Details of the circuit operation and component connections are available from National Semiconductor [5].

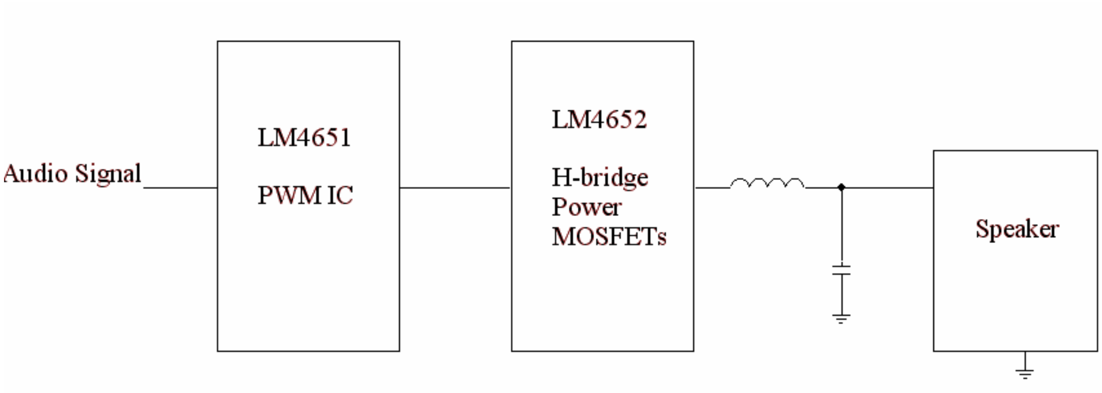

Figure 2. Block diagram of the National Semiconductor LM 4651 and LM 4652 ICs and a low-pass filter used to implement a class-D amplifier.

The third approach was to design a class-D amplifier from basic circuit components. The design consisted of a preamplifier (operational amplifier) for the audio signal, a triangular-waveform generator (ICL8038, Intersil) for the high-frequency carrier signal, a high-speed comparator (AD8561 Analog Devices), a MOSFET driver IC (HIP4080, Intersil), and discrete power MOSFETs (IRFZ44N, International Rectifier) connected as an H-bridge, as shown in Fig. 3. The carrier frequency was chosen to be 100 kHz. An output filter was not used because the inherent frequency response of the speakers provided adequate filtering. The design was assembled on a breadboard. The volume was adjusted by varying the supply voltage to the H-bridge.

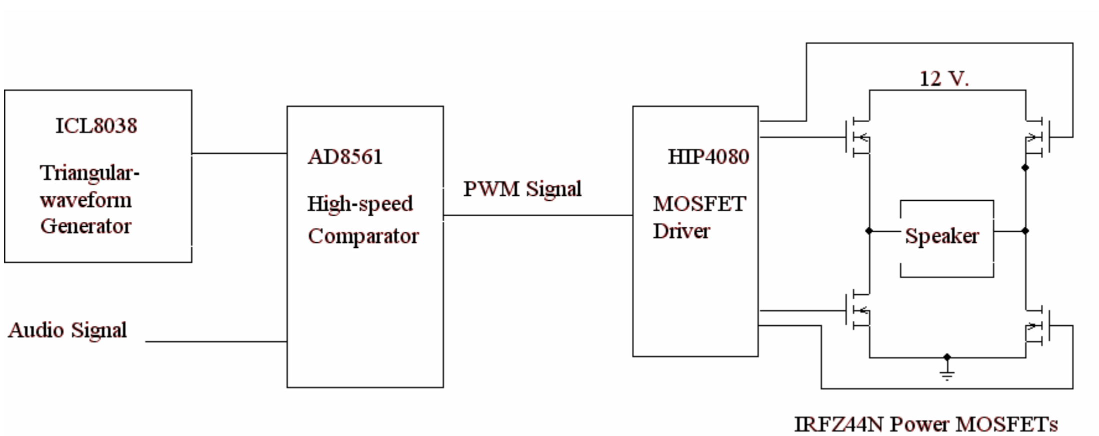

Figure 3. A class-D amplifier implemented with basic components. Students reported the most positive learning experience with this circuit.

Although circuit performance of this student-designed amplifier did not achieve the quality of a commercially viable product, results were quite impressive. Output volume was empirically evaluated as "earsplitting." The power MOSFETs remained cool to the touch, indicating high efficiency. Audio quality was judged by the students to be satisfactory. If there had been more time available in the semester, efficiency and total harmonic distortion (THD) measurements would have been taken.

Conclusions

Students who worked with the Texas Instruments class-D evaluation boards reported that the boards were fairly straightforward to operate and were a good demonstration of class-D amplifiers. The evaluation boards can be used for a one-laboratory experience or for a classroom demonstration. However, the students who designed a class-D amplifier from basic building blocks (Fig. 3) reported the most positive learning experience and greatest satisfaction compared to those who chose to investigate amplifiers and components that were more self-contained (Fig. 1 and 2).

Students reported that the design and implementation experience was uniquely valuable. Details of circuit layout and nonideal behavior of real components were experiences not gained to this degree in previous laboratories. One student wrote: "This is the first project I've ever worked on where the details and quality of the circuitry really affected performance." All students who participated in the class-D project portion of the power electronics course rated their experience as excellent.

Judging from the enthusiasm exhibited by these students and the amount of theory and practical knowledge learned, I recommend that class-D amplifier design and experimentation be included in undergraduate power-electronics courses.

Acknowledgments

We are grateful to Mr. Greg Hupp of Texas Instruments for his excellent introduction to class-D amplifiers and to Texas Instruments for use of their TPA005D02 class-D evaluation modules. Appreciation is also given to students Eric Andris, Dave Wright, Jason Janulis, Everett Jones, and Bob Dysert for their extra work in my power-electronics course.

Bibliography

[1] Hart, Daniel W., *Introduction to Power Electronics*, Prentice-Hall, 1997

[2] Mohan, Undeland, and Robins, *Power Electronics: Converters, Applications, and Design*, third edition, John Wiley & Sons Inc., 2003

[3] Dapkus, Don, and Chen, Robin, "High-efficiency Audio Amplification Using Class-D Audio Power Amplifiers," IIC-Taipei Conference Proceedings, 2000

[4] "TPA005D02 Class D Stereo Audio Power Amplifier Evaluation Module", Texas Instruments, www.ti.com, 1998

[5] "LM4651 & LM4652 Overture™ Audio Power Amplifier 170W Class D Audio Power Amplifier Solution," National Semiconductor Corporation, www.national.com, March 2004

DANIEL W. HART is a professor of electrical and computer engineering at Valparaiso University in Valparaiso, Indiana. His teaching interests include linear circuits, microelectronics, and power electronics. He is author of the textbook *Introduction to Power Electronics* (Prentice-Hall).