Better Than Class D: Predictive Energy Balancing Can Boost Efficiency And Fidelity Of Cell Phone Audio Amplifiers

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CogniPower originally developed Predictive Energy Balancing for control of switched-mode power converters. Conventional switched-mode power converters require delicate compensation because feedback from the output is delayed by the action of the output filter. As long as that delay is present, controls cannot act immediately without inducing oscillation. Various ways to deal with that limitation are discussed in the literature, but all of them involve a compromise between stability and agility.

CogniPower Predictive Energy Balancing provides the first and only control method to avoid that compromise. The key is to make the switching decision based on the eventual outcome of that decision, which can be calculated in advance using fundamental energy equations. In the process, the unavoidable delay of the output filter is effectively removed from the feedback loop. PEB allows the maximization of both agility and stability.

Class D power amplifiers are a more-efficient alternative to linear amplifiers. Because they are switching amplifiers, they are subject to the same control limitations that apply to switched-mode power converters. Harmonic purity is essential for an audio amplifier. The art of building a good class D audio amplifier revolves around removing unwanted harmonics, distortion, and noise from the audio output.

As it happens, Predictive Energy Balancing is a powerful tool for achieving those ends. Because PEB allows an output to be regulated precisely on a cycle-by-cycle basis, instead of on the average, PEB enables an entirely new form of switched-mode amplifier. This article describes the operation of a PEB audio amplifier, comparing the efficiency and fidelity of this new amplifier design against conventional class D audio amplifiers.

This discussion is mainly oriented toward the types of amplifiers used in cell phones and other handheld consumer devices where there are opportunities to significantly improve audio performance, while improving efficiency and meeting cost goals. The PEB amplifiers described here are covered by four issued US patents. Additional patents are pending.

Understanding PEB Amplifier Operation

The following block diagram shows one version of this new class of amplifier (Fig. 1.) It is similar to the H-bridge, or bridge-tied load (BTL), configuration of a class D amplifier, but with some of the components rearranged, and with different controls.

![Fig. 1. Block Diagram of a PEB amplifier. This version resembles the H-bridge configuration of a class D amplifier, but with a different arrangement of components and different controls.](image-url)
The amplifier in Fig. 1 is a bidirectional flyback amplifier. Energy is moved from the battery to the output using PEB flyback conversion. Energy is moved from the output to the battery by reverse flyback conversions. The PEB calculations are done in real time by the circuitry on the left side of the block diagram. These calculations and the means to perform them are described in detail in the reference.

The circuitry on the right in Fig. 1 is two ordinary totem poles forming an H-bridge. Class D audio amplifiers would have the speaker in place of L1. Here, the speaker is placed between the output and the power supply. A piezo speaker is shown in this example. Piezo speakers are known for efficiency at the expense of sound quality. A PEB amplifier can maximize efficiency while improving the sound output of a piezo speaker. The same PEB amplifier can drive a dynamic speaker with many of the same benefits.

The inductance in a PEB amplifier is active at the switching frequency, so a much smaller inductor serves the purpose, compared to the inductors needed to filter at audio frequencies. These amplifiers can be fully bipolar, or can be offset to drive the output above and below the power supply voltage. The speaker shown above is connected in the second fashion. The speaker could just as well be connected between the output and ground with a coupling capacitor to remove the dc bias voltage.

**Comparing PEB And Class D Amplifier Performance**

The most efficient form of Class D amplifier is the half-bridge configuration, so we will use that amplifier form as the point of departure for comparing efficiency. The basic class D amplifier is shown in Fig. 2. For this comparison, 8 Ω is used for the filter resistor. That resistance is the largest single cause of power loss in such amplifiers. 8 Ω is a typical minimum value needed for stability when driving a piezo speaker.

![Class D Amplifier](image)

*Fig. 2. Basic class D amplifier.*

For simplicity, the output is shown here as unipolar. In practice, it will be undesirable to allow several volts of dc bias voltage on the speaker. Either an ac coupling capacitor would be used, or the other end of the speaker would be returned to a mid-point voltage. Either way, the efficiency will be about the same.

Fig. 3 shows a comparison of PEB amplifier performance versus that of a class D amplifier in SPICE. To unequivocally show the difference in energy consumption, both versions are simulated operating from a pre-charged capacitor as the power supply. Both are running internally at 200 kHz and are driving a 1-μF capacitor. That capacitive load approximates the behavior of a cell phone piezo speaker. The audio output is a 2-kHz sine wave at 2.5 V peak-to-peak. Both the PEB amplifier and the class D amplifier reproduce the sine wave, as seen in the upper axis.
Because the class D amplifier has almost no power supply rejection (PSR), you can see the output amplitude diminish as the supply voltage is drawn down. The PEB amplifier, on the other hand, has good PSR, so no such effect is evident. The PEB amplifier shows less ripple, and less phase shift than the class D alternative. If even better fidelity is required, for the PEB case, a small additional low-pass filter placed after the feedback can selectively remove the remnants of the carrier frequency without disturbing the dynamic response.

Adding more filtering to the class D version is more difficult. You cannot simply continue to enlarge the inductive filter without causing non-linearity in the audio range. Adding a second filter pole compounds the difficulties caused by interactions between the reactive elements. The remaining choice is to increase the series resistance, which adds phase shift and further reduces the efficiency.

The energy consumed by the class D amplifier over the 3-ms period shown in Fig. 3 is 40 mJ. The PEB amplifier, consumes 1 mJ over the same period while producing a superior output. This simulation (and subsequent simulations described here) does not account for any mechanical work done by the speaker, so the actual efficiency in both cases will be reduced. Still, piezo speakers do behave very much like ideal capacitors. That greatly improved efficiency is not imaginary. It derives from efficient energy recovery and from eliminating the need for dissipative series resistance.

The preferred form of class D amplifier for portable audio applications is the bridge-tied load (BTL). These amplifiers are more tractable, but less efficient. The BTL form doubles the voltage swing available at the output, which can eliminate the need for an additional power supply voltage. The ac coupling capacitor used in the half-bridge form also disappears. There is a filterless variant of this structure, but it is even less efficient because the speaker itself must absorb higher frequency energy that is well outside the audible range.

The filterless variant requires the speaker to be reactive at high frequencies in order to maintain reasonable efficiency. Also, connections to the speaker carry square waves, and radiate electrical interference. The disadvantages of the filterless form are tolerated in order to eliminate the large filter inductors otherwise needed. The PEB amplifier eliminates those bulky filter inductors without stressing the speaker or compromising efficiency.

Fig. 4 is a block diagram of a simplified BTL amplifier, with filtering, driving a piezo speaker (shown as a 1-µF capacitor.) In this case, the 8-Ω series resistance is split into two 4-Ω resistors. Again, that is a typical minimum value needed for stabilizing circuits of this sort. Fig. 5 shows the performance and efficiency of the BTL form in comparison to the same PEB amplifier.
When its configuration was changed from half-bridge to bridge-tied load, the class D amplifier's power consumption rose from 40 to 54 mJ due mainly to the additional switches in the path. (For simulation purposes, all the switches used here have a 50-mΩ on-resistance.) Note that the inductive filters required here for efficiency are physically large. They also have a tendency to interact adversely with inductive or capacitive loads. Piezo speakers have a resonant frequency, often around 1 kHz. That resonant tendency will add distortion and harmonics, and cause a peak in the frequency response curve. The PEB amplifier, in contrast, works to actively damp such resonances without distortion or inefficiency.

To illustrate, here is an extreme case. A simulated current source oscillating at 5 kHz with an amplitude of ±30 mA is connected across the speaker. In Fig. 6, the class D amplifier output is badly distorted as a result. The PEB amplifier is barely affected at all. That result carries extra significance because the active damping provided by PEB reduces the need to mechanically damp the speaker. Mechanical speaker damping adds size and cost and reduces efficiency.
The additional current load is centered on zero, so it does not change the average efficiency. You can see the additional perturbations on the energy consumption waveforms. Implicit in Fig. 6 is that the PEB amplifier will drive inductive loads with equal ease. A dynamic speaker can be placed in parallel with a piezo speaker with little or no change in dynamic behavior. If a dynamic speaker is to be used with a PEB amplifier, a capacitor should be placed across the output. The capacitor acts to filter the operating frequency, and sets the scaling for the PEB controls.

Class D amplifiers require careful regulation and decoupling of the power supplies because power supply noise in the audio band comes right through to the output. Also, dc power shifts are seen as gain changes in class D amplifiers. Fig. 7 clearly shows the problem. In some cases, extreme measures are needed to address these issues. The PEB amplifier has excellent power supply rejection, further simplifying system design while improving sound quality.
The BTL structure doubles the voltage available at the speaker, but piezo speakers may need more than 8 V for best operation. For a class D amplifier, an extra power supply rail must be generated. That involves another dc-dc conversion, with the associated increases in size, cost and inefficiency. The PEB amplifier, in contrast, can produce arbitrarily high output voltages.

Fig. 8 shows a simulation with 15-V peak-to-peak output while running from the same 4-V supply. The energy consumption goes up with the output voltage, but the PEB energy consumption at 15-V is still less than the BTL amplifier’s consumption at 2.5-V peak-to-peak output.

Another set of limitations of the class D amplifier is more evident at lower frequencies. Fig. 9 is a detail of a 200-Hz output signal. This comparison is identical to the 2-kHz comparison of Fig. 5 except for the lowered audio frequency. The class D output exhibits unwanted higher frequencies riding on the audio signal. This harmonic distortion falls squarely in the audible range. Nonlinearity in the filtering components makes these problems difficult to address. Note the complete absence of such distortion in the PEB case.
Because the PEB amplifier is, in essence, a power converter, its bandwidth extends at the low end to dc. That might not be of much value in a handheld device with a minimal speaker. In a high-fidelity audio system, the ability to reproduce very low frequencies is a bonus. The high end of the frequency range is determined by the operating frequency. For best high-fidelity response at the top of the audio range, the PEB amp should run internally at or above 250 kHz.

Note that it is easy to change the clock frequency, because the PEB calculations do not rely on a given operating rate. For a cell phone amplifier, audio quality above 10 kHz is not an issue, so a lower operating frequency is entirely adequate. In general, PEB amplifiers can run at less than half the speed required for class D amplifiers, for higher efficiency. The clock rate could even be adaptive for maximum power savings.

An additional advantage provided by the bidirectionality of a PEB amplifier is an inherent energy harvesting ability. A speaker may not be an optimal transducer for energy harvesting, but a significant amount of energy can be recovered from ambient sound and vibration in a noisy environment, such as in a car or an airplane cabin. Given that bidirectional ability in the amplifier, combined with the PEB amplifier's ability to actively damp resonances, cell phone speakers could be designed to be more effective transducers for energy harvesting.

The ability to bidirectionally drive a variety of speakers opens possibilities for high-fidelity applications. High-quality speakers require enclosures to damp the resonances that cause peaks and valleys in sound reproduction at different frequencies. The CogniPower audio amplifier can remove those peaks and valleys actively, by recovering energy. That method contrasts with the conventional, passive damping approach that can waste large amounts of power.

Also, ceramic or electrostatic speakers are more efficient, but are hard to drive using conventional amplifiers. A PEB amplifier can recover even more energy from these types of speakers. For amplified speakers of any sort, a PEB amplifier will enable better efficiency from smaller speaker enclosures while improving sound quality and lowering cost.

The comparisons shown here are SPICE simulations generated in LT SPICE. We have found excellent correspondence between SPICE and the bench. To illustrate, Fig. 10 is a simulation of the PEB amplifier driving a piezo speaker at 8 V, 10 kHz. Fig. 11 is a screen shot from a Yokogawa DLM2000 oscilloscope probing the evaluation board. Note that the clock in the evaluation board is running 20% faster than the theoretical rate. Instead of the 20 control cycles per input cycle seen in SPICE, there are 24 cycles on the bench.
Fig. 10. Simulated PEB amp operation.

Fig. 11. Observed PEB amplifier operation.
**Demo System Performance**

The PEB amplifier demo board was designed with handheld audio devices in mind (Fig. 12.) The distortion and noise levels, as tested, came out far better than existing amplifiers for portable audio. That extra fidelity can enable the same PEB amplifier that drives a built-in speaker to drive a high-fidelity headphone output. Even before attempting to optimize for a high-fidelity application, we measure less than 0.1% distortion at 1 kHz. The noise floor is near -90 dB and the harmonic content is minimal (Fig. 13.) Audiophile-quality test equipment would be necessary to fully explore the capabilities of the demo board.

Because the demo system is constrained by the need to operate at the low battery voltage of a cell phone, its performance does not represent the limits of the predictive approach to switched-mode amplifiers. There is every reason to expect that a version of the amplifier running on 5 V instead of 3.5 V could reach 0.01% total harmonic distortion. When the controls are optimized for fidelity, even better performance will be achievable.

*Fig. 12. Evaluation board for Predictive Energy Balancing amplifier.*
**Conclusions**

Cell phones and tablet computers are known for sharp displays and fuzzy sound. CogniPower Predictive Energy Balancing audio amplifiers can improve both their efficiency and fidelity. To make this approach practical, fundamental new control technologies are necessary, explaining why it has not been done before. These new control technologies would not have been possible without the recent improvements in solid-state power switching components. Further, the simulation technology to develop these techniques would have been prohibitively slow and expensive not that many years ago.

A predictive, bidirectional power converter drives the speaker directly with an analog signal, eliminating extra power supplies and reactive filters. The bidirectional predictive amplifier approach makes a given speaker sound better, and enables the design of more-efficient speakers. These efficiency and performance benefits can be realized without an increase in cost. In fact, system costs can be reduced by simplifying and shrinking the circuitry, by generating less waste heat, or by using a smaller battery to perform the same job.

The same audio amplifier technology can be scaled for hearing aids, or consumer electronics, all the way up to theater-sized systems. Related versions of this CogniPower technology can be adapted to power converters and motor drives as well as other power amplifier applications.

**Reference**

About The Author

Tom Lawson has been involved with instrumentation since 1968. During the 1970s he worked in medical electronics with Bill Morong, the principal inventor of predictive energy balancing. During the 1980s and 90s he built his own instrumentation company. Since rejoining Bill Morong, Lawson’s focus has been on power conversion. Lawson started CogniPower in 2009 to begin the commercialization process. Lawson is named on eight issued patents and five patents pending, spanning four decades.

For more on power supply control methods, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category, and select “Control Methods” in the Design Area category.