# Predictive Energy Balancing for Agile Control of Switched-Mode Power Converters

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The number 6 billion turns up often as the number of cell phones in use worldwide. Published estimates average to around 25 power converters per cell phone. If the typical switching frequency is 50 kHz, that works out to 7.5 x 10^15 switching decisions per second in cell phones. Add in computers and file servers and consumer goods and motor controls and the number of switched-mode power decisions made daily is astronomic.

You might think such frequent decisions would be based on the best information available, but that is generally not the case. Take a basic flyback converter:

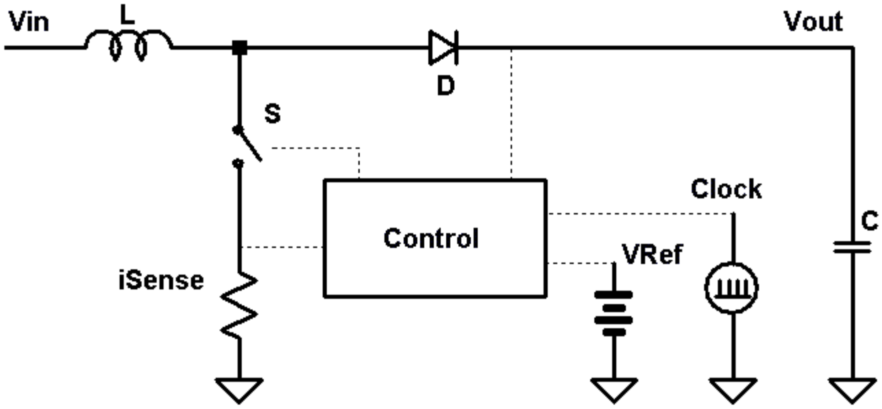

Figure 1  Basic Flyback Converter Block Diagram

When switch S is closed, inductor L is energized from the voltage source, Vin. When the switch is subsequently opened, that inductive energy passes through Diode, D, into filter capacitor, C. Ideally, one would want to switch from energizing the switched inductor to transferring energy to the output, Vout, at the instant that would result in the best regulation. Typically, the decision is based instead on what was happening, on the average, during some previous time period. The result is that such regulators under-respond to step changes at first, and then over-respond afterward. To mitigate the problem, compensation is used to change the gain during disruptions. Compensation can involve a little or a lot of calculation or circuitry, but it always involves a compromise between stability under DC conditions and improving transient response under AC conditions. Since positive feedback in power converters can cause destructive runaway, careful attention must be paid to compensation. But, there is a better way. Let's go back to the ideal case:

Ideal Step 1: Energize the inductor to the correct level for best regulation.

Ideal Step 2: Transfer that inductive energy to the output filter, resulting in the output voltage reaching the regulation point.

The ideal case may seem to require a preternatural ability to predict the future, but the underlying physics provide the key. There is a relatively simple calculation, based on the fundamental energy equations, that can determine just when the correct amount of energy has been loaded into the switched inductor.

The amount of energy required to supply to the output is the difference between the instantaneous kinetic energy at the output filter capacitor and the desired kinetic energy at the output filter capacitor:

$$\mathbf{KEC = (V^2 \times C) / 2}$$

Where: KEC = capacitive energy in joules
V = voltage in volts
C = filter capacitance in farads

$$\mathbf{KEReg = (Reg^2 \times C) / 2}$$

Where: KEReg = desired energy in joules
Reg = Reference point in volts
C = filter capacitance in farads

The difference is energy demand:

$$Demand = KEReg - KEC$$

The kinetic energy in the switched inductor is:

$$\mathbf{KEL = (I^2 \times L) / 2}$$

Where: KEL = inductive energy in joules
I = current in Amps
L = switched inductance in henries

The inductive term is the energy Supply. When Supply equals Demand, it is time to stop the energizing period and to begin the transfer period.

Each control cycle is then self-contained. There is no history (integral) or rate sensitivity (differential). The gain becomes a function of the ratio of the switched inductance to the filter capacitance.

We call this process Predictive Energy Balancing (PEB). A block diagram of circuitry to perform the calculation appears here (Fig 2). The VSCALE input adjusts for the L/C ratio. The same, or similar, computational block can control a flyback or forward converter, a discontinuous buck converter, or a switched-mode power amplifier. The calculations scale for any size power converter. With one or two more energy terms, Continuous Mode converters can be controlled, too. Note that the energy balance calculations can be made in an analog or a digital fashion.

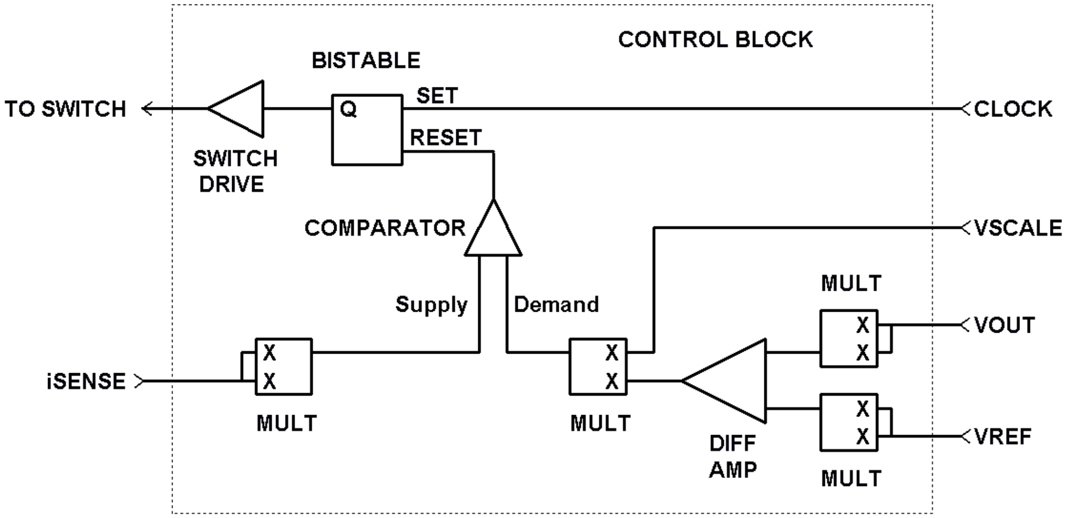

Figure 2 Predictive Energy Balancing Flyback Converter Control Block Diagram

The best conventional power converters respond to a load step in six control cycles. PEB controls respond in a single cycle. That might not sound like a dramatic difference, but it changes the ground rules for what is practical when controlling switched mode power. Because of the averaging which takes place over those six control cycles, there is an inevitable time delay which introduces a tendency to alternately overcorrect and undercorrect. That oscillatory tendency generates sub-harmonics.

Predictive Energy Balancing eliminates the need to compromise between stability and agility. The smallest theoretic filter capacitors can be used. Because of the intrinsic stability, catch diodes and protection circuits can be reduced or eliminated. Because there is no averaging in PEB, the controls can be synchronous or asynchronous, and a synchronous clock frequency can be adjusted at will. Because the controls are based on the underlying physics, and do not require compensation, they accept a wider range of operating conditions. That makes PEB control convenient for digital power.

To illustrate the capabilities of PEB, CogniPower built a power converter in the form of an audio amplifier. (Imagine what would happen if you asked a conventional power converter to track an audio signal.) PEB is agile enough to reproduce a 20 kHz sine wave with excellent fidelity while driving a load that is capacitive, inductive or resistive in any combination. The PEB amplifier was demonstrated live at APEC 2013, in Long

Beach, CA.

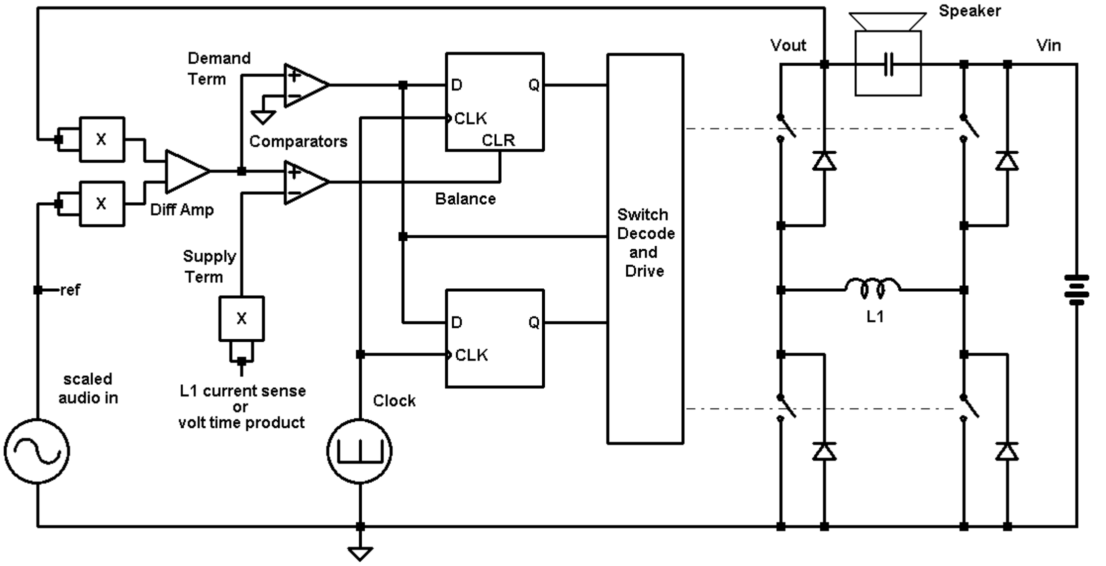

Figure 3 PEB Audio Amplifier for Driving Cell Phone Piezo Speaker

Figure 3 shows an efficient PEB power converter that doubles the drive voltage available (similar to a bridge-tied load Class D amplifier). Four ordinary FET switches form two totem poles. When the magnitude of the output is increasing, energy is predictively transferred from the battery to the speaker capacitance. When the magnitude is decreasing, energy is deterministically transferred from the speaker to the battery.

CogniPower set out to build a proof-of-concept demonstrator for voice-quality audio, and found instead a high fidelity amplifier. Distortion has been measured at 0.1%. The screen shots here are from a Yokogawa DLM2000. The sine wave reference, in purple, is 10 kHz. The output is the yellow trace. Current in the switched inductor is shown in green.

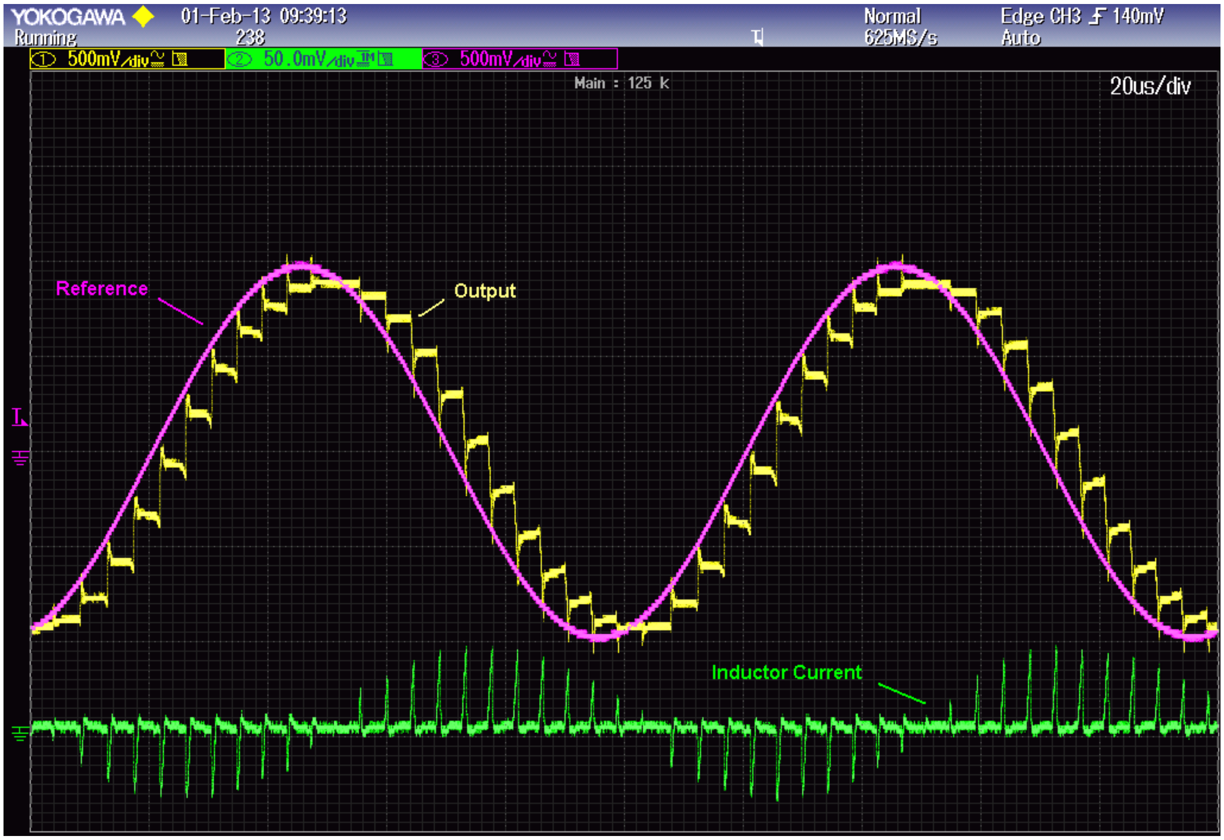

**Figure 4 PEB Amplifier Screen Shot Reproducing a 10 kHz Sine Wave**

The regulation points are reached with good accuracy on both the increasing and decreasing portions of the waveform. Note that a notch, or low pass, filter placed after the feedback will remove the chopping frequency from the output. You probably do not need your power converter to make music, but you may be burdened by sub-harmonic behavior. That is absent from a PEB converter.

To illustrate, the same demonstration system will act as a DC/DC converter. With a DC reference and a 10 kHz AC load, a very similar current waveform will be seen as the output is held at the desired DC level. In Figure 5 the load is shown in purple. The output in yellow, AC coupled for the oscilloscope, is held constant. The inductor current, in green, reflects the bipolar sinusoidal AC load.

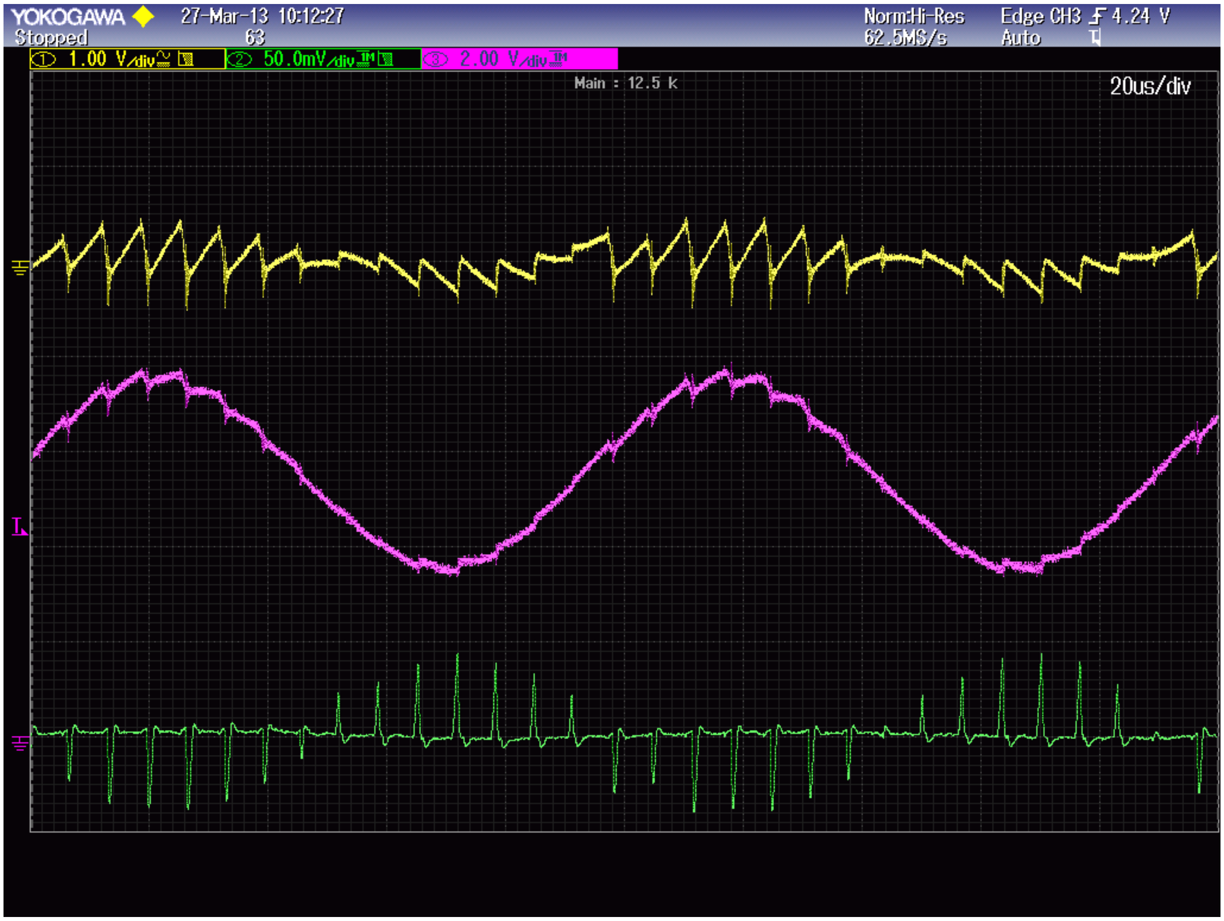

Figure 5 PEB amplifier with DC Output and Sine Wave Load

The next screen shot is of a more familiar type. The load is unipolar, changing from approximately 20% to 80% of full load. This time the load is a square wave, again at 10 kHz. The output filter capacitor here is only 470 nF which is appropriate for amplifier application. For a DC/DC power converter, 800mv of output ripple would likely be excessive. However, a 10µf filter would result in 40 mv of ripple. The converter is running at 166kHz in Figure 6. It will operate comfortably at over 5 times that rate, so the output ripple can be just a few mv, if required.

The more important thing to note regarding Figure 6 is the single-cycle regulation. The fastest Pulse Width Modulated (PWM) power converters settle in 6 cycles after a step change. Under these conditions, a PWM converter would never reach proper regulation.

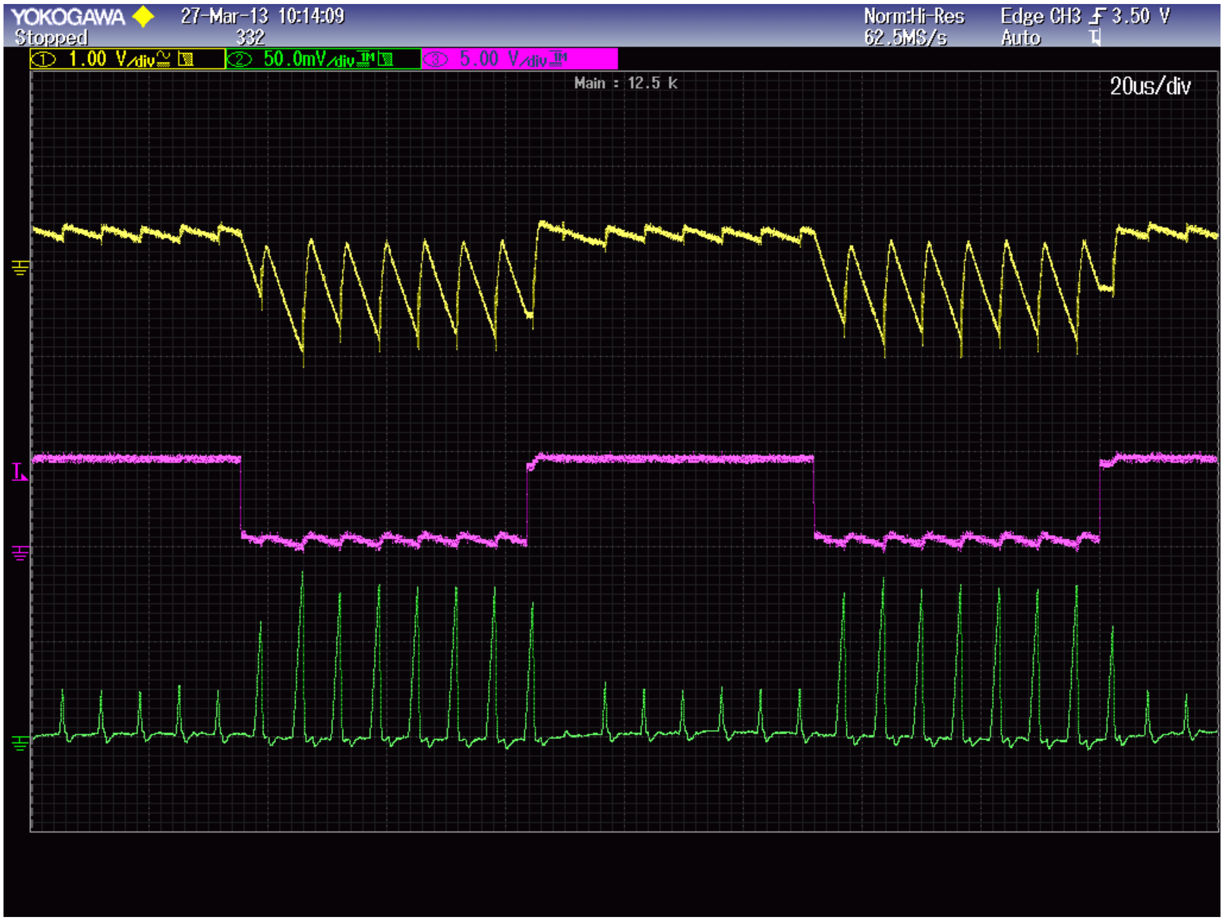

**Figure 6 PEB Amplifier Running as a DC/DC Converter with a Step Load**

There is an operational difference to keep in mind when applying PEB. The dynamic gain is determined by the ratio of L to C. If the ratio of the switched inductance to the filter capacitance isn't known, or, if it can change significantly during operation, a conventional feedback loop should be added to set the predictive gain. That conventional loop can be very slow and have very little gain, so that it can only tune the PEB behavior over a long period, but will not interact with the dynamic response.

The bidirectional nature of the PEB audio amplifier makes it as efficient as the best Class D amplifiers while the distortion is that of a good linear amp. In general, PEB can offer incremental efficiency gains when replacing conventional power converters, but can provide larger gains in cases where entire stages of power conversion can be eliminated.

## Conclusions

When near-ideal cycle-by-cycle switching decisions are made, the first advantage for PEB control is best transient performance. That advantage is evident in the elimination of a compromise between stability and agility. Intrinsic stability reduces the need for added protection components, and brings reliability benefits. Additional benefits can be achieved depending on design priorities. Possibilities include smaller filter capacitors, flexible switching speeds, increased efficiency, increased operational range, ease of digital control, and compatibility with aggressive power management techniques. Because there are fewer assumptions built into the hardware, PEB converters can be adapted to new applications with less engineering effort. The absence of compensation simplifies development and testing.

After the integration of PEB controls, expect a size and cost advantage, as well. Circuitry for performing Predictive Energy Balancing is simpler than that required for the more computationally intensive compensation schemes. The PEB Audio Amplifier is covered by four issued US patents with overseas patents pending.