Power Management for Portable Audio Applications

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Outline

- Power Management for Portable Applications
- Self-Optimization in DC-DC Converters
- Optimized Efficiency Through SOS
- Application of Predictive Feedforward: Miniature Class-D Audio Amplifier
- Conclusions
Traditional Power Management (e.g. ACPI) is basically a **one-way** decision.
Power Management for Portable Applications

- The load must be able to **communicate** to the power supply and optimize power use.
Target Application: Handheld Devices

- DC-DC converter provides a regulated bus voltage for digitally fed predictable load
- In general, the digitally fed load may be a speaker, display, ICs etc.
- Goal: on-the-fly optimization of DC-DC converter performance
- $2.6 \, \text{V} < V_{\text{batt}} < 4.2 \, \text{V}$ (single cell lithium Ion)
- $I_{\text{batt}} < 1 \, \text{A}$

![Diagram of Power Management System]

- Battery
- DC-DC
- Digital Signal Source
- DSP/DAC
- Amp
- Load
- Digitally Fed Load
- $v_{\text{bus}}$
- $i_{\text{bus}}$
- $Z_{L}$
Self-Optimization in DC-DC Converters

There exists numerous digital/analog schemes for on-line optimization of:

- Efficiency: $R_{on}$, $Q_{gate}$, dead-time, multi-mode (PFM, DCM etc.)
- Dynamic response: compensator coefficients, auto-tuning etc.

How is it achieved in current technology?
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This Work: Load Prediction Concept

- Premise: *digitally fed load has predictable load impedance*
- Sensor-less approach:
  - Data stream is used to optimize DC-DC converter efficiency in real-time
Optimized Efficiency Through SOS

- Optimum gate width varies with load power:

\[ W_{opt} \propto \frac{P_{out}}{\sqrt{f_s}} \]

\[ P_{gate} = f_s \left( C_{gate,N} V_{in}^2 + C_{gate,P} V_{in}^2 \right) \]

\[ P_{cond} = \left( I_{out}^2 + \frac{\Delta i_L^2}{12} \right) \left( D R_{ds,P} + D' R_{ds,N} \right) \]

\[ \eta \]

\[ W_1 < W_2 < W_3 \]

\[ C_{gate} \text{ vs. } R_{ds} \]

Log (I_{out})
SOS Implementation

- “Switched-W” concept can be expanded to multi-gate binary-weighted (segmented) output stage:

- Active area is identical to traditional output stage
Trade-off Between $R_{on}$ and $P_{gate}$

- When changing from $[111]$ to $[001]$:
  - $P_{gate}$ is reduced by $6.3 \times$
  - $R_{on,N}$ increased by $2.4 \times$, $R_{on,P}$ increased by $3.1 \times$
Efficiency Measurements @ 4 MHz, $V_{in} = 2.7$ V

- Peak efficiency at 4 MHz is limited by high switching losses in the output stage + inductor conduction losses ($> 90\%$ @ 2 MHz)

![Graph showing efficiency measurements](image-url)
Application of Predictive Feedforward: Miniature Class-D Audio Amplifier
**All-Digital Hi-Fi Open Loop Class-D Amplifier**

- Why class-D? Efficiency, Size, Cost
- Operates as a high-bandwidth *open-loop* DC-DC converter with variable $V_{out}$
- Open-loop class-D amplifier:
  - All digital
  - Well suited to digital audio sources
- Local feedback may be added to suppress distortion due to output stage non-idealities

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![Diagram of All-Digital Hi-Fi Open Loop Class-D Amplifier](attachment:diagram.png)

- **PCM Data**
  - ~ 24-bits
  - 44.1 kHz

- **FIR Oversampling**
  - ~ 4x-16x
  - ~ 4th-10th order

- **ΔΣ Modulator**
  - ~ 8-10 bits
  - 100-500 kHz

- **DPWM**

- **Class-D Output Stage**
  - $V_{bus}$
  - $V_{bus}/2$
  - 4-16 Ω

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All-Digital Hi-Fi Open Loop Class-D Amplifier

- H-bridge class-D amp is preferred
  - Improve PSRR
  - Eliminate need for negative rail or AC coupling cap

\[
P_{\text{max}} = \frac{4V_{\text{bus}}^2}{R}
\]
All-Digital Hi-Fi Open Loop Class-D Amplifier

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Estimating The Class-D Amplifier Load Current

- Class-D input current is proportional to output power (non-linear):

\[ P_{out} = \frac{i_{spk}(t)v_{spk}(t)}{V_{bus}\eta} = \frac{I_{spk}V_{spk}}{2V_{bus}\eta} (\cos \phi - \cos(2\omega t + \phi)) \]

- Crude resistive speaker approximation:

\[ i_{bus}(t) = \frac{V_{spk}^2(t)}{V_{bus}\eta R} \propto V_{spk}^2(t) \propto s[m]^2(t) \]

Component at 2f

Speaker voltage can be obtained directly from audio data stream!
DC-DC Converter + Class-D Amplifier

- Prototype system includes 2 custom ICs + off-the-shelf parts
**DC-DC Converter + Class-D Amplifier**

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DC-DC Converter + Class-D Amplifier

- Prototype system includes 2 custom ICs + off-the-shelf parts

![Diagram of DC-DC Converter + Class-D Amplifier]

- Battery voltage range: 2.7V - 4.2V
- Segment Controller
- Digitally Controlled DC-DC Converter
  - $f_s1 = 4$ MHz
- Digital Fed Load
- Gate Driver
- Class-D Output Stage
- 8x FIR Oversampling
- Modulator
- PLL
- DPWM & Dead-Time
- $f_s2 = 44.1$ kHz
- $8f_s2 = 352.8$ kHz
**Segment Controller**

- Segment controller estimates class-D load current as a resistive approximation.
- Enable code is calculated each audio sample \( f_{s1} = 44.1 \text{ kHz} \).
- Hysteretic thresholds are encoded into a lookup table.
- Enable codes are calculated and transmitted asynchronously to the buck converter.

\[
i_{bus}(t) = \frac{V_{spk}^2(t)}{V_{bus}\eta R} \propto V_{spk}^2(t) \propto s[m]^2(t)
\]
**Digitally Controlled Buck Converter**

- Simple digital LUT-PID based compensator is used with $f_{s2} = 4$ MHz
- Output stage is re-configured according to data from segment selector

Diagram of Digitally Controlled DC-DC Converter.
Experimental Results

- High speed flash D/A is used to compare predicted bus current $i_{pd}[n]$ with actual bus current $i_{bus}(t)$ during audio playback.
Experimental Results

- Good agreement between the predicted and actual bus current is achieved despite the complex speaker impedance.
Experimental Results

- Output stage is dynamically re-sized according to predicted speaker current.

**Speaker Voltage:**
- Predicted Current:
- Segment Codes:

![Graph showing predicted current and segment codes](image)

- PFM Mode
- Dynamic Optimization

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PFM → PWM Operation

- Output stage is dynamically re-sized according to predicted speaker current

Predicted Current:

Bus Voltage (AC):

Segment Codes:

ch1: $i_{pd}[m]$

ch2: $v_{out}(t)$

PFM Mode ↔ PWM Mode
**PWM → PFM Operation**

- Output stage is dynamically re-sized according to predicted speaker current

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**Predicted Current:**

**Bus Voltage (AC):**

**Segment Codes:**

![Graph showing PWM and PFM Modes](image)

- **PWM Mode** ↔ **PFM Mode**

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Total Energy Consumption Comparison

- The energy savings is highly dependent on the power distribution of the music sample
- For a given dynamic range, the power savings depends on the amount of time spent in each power bin
  - Rock music has the lowest energy savings (most time spent with seg = ‘111’)
  - Jazz music has the highest energy savings

<table>
<thead>
<tr>
<th>Song Type</th>
<th>Length (s)</th>
<th>Total Energy Consumption (J) @ V_{batt} = 3.6 V</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rock</td>
<td>149</td>
<td>11.16 (PWM Mode, All segments ON) 8.80 (Automatic Segment / Mode Control)</td>
<td>21.15</td>
</tr>
<tr>
<td>2. Classical</td>
<td>380</td>
<td>23.77 7.08</td>
<td>27.70</td>
</tr>
<tr>
<td>3. Jazz</td>
<td>140</td>
<td>11.16 8.80 17.18 4.36</td>
<td>38.32</td>
</tr>
</tbody>
</table>
Segment Distribution

- # of samples for each segment code can be determined through audio post-processing

- Audio sample:
Conclusion and On-going Work

- Demonstrated a feed-forward concept to improve energy efficiency in portable applications
- Experimental results reported for a miniature Class-D amplifier
- Maximum of 38 % in total energy savings was achieved
- Energy savings depends on dynamic content of music
- Effect on distortion?