Modeling DC-DC Converter Efficiency and Power Management in Ultra Low Power Systems

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Ultra Low Power SoCs (like BSN)

Features
• Comprehensive and unobtrusive human health monitoring.

Needs
• Small Form Factor, light weight
• Long battery life/ run on harvested energy
• Low cost.
• Efficient Power Management

Ex: Fan Zhang et al. "A batteryless 19μW MICS/ISM-band energy harvesting body area sensor node SoC." ISSCC 2012
Power Management Techniques

• Power Management techniques are commonly employed to increase the life-time of ULP system ex. DVFS, Clock gating, Power gating etc.

• These techniques have an impact on the efficiency of DC-DC converter, ex. DVFS changes load and output voltage of the converter.

• The benefits of these techniques cannot be established in isolation from DC-DC converter.

• In this talk we present a model and a framework to correctly study the benefits of Power Management techniques in conjunction with DC-DC converter.
Outline

- Model of DC-DC converter
- Framework to obtain energy cost
- Block level Power Management Technique
- Results
Model of a DC-DC converter

• Efficiency of DC-DC converter decreases at both light load and heavy load (considering PWM scheme)

\[ P_{\text{LOSS}} \propto aI_L + b/I_L \]

• Efficiency peaks at a given load and decrease on either side.

• We model Efficiency with load current as

\[ \eta_i = \eta_2 - (\eta_2 - \eta_1) \cdot (\log(I_L/I_O))^2/4 \] …………………(i)

Where \( \eta_2 \) is the peak efficiency occurring at load \( I_0 \), \( \eta_1 \) is the minimum efficiency at a given load.

• For a buck converter, the efficiency of a converter decreases linearly as the output voltage decreases

\[ \eta_v = \eta_1 + m \cdot (V-V_{\text{min}}) \]
Model of a DC-DC converter

\[ \eta = \eta_v \cdot \eta_i \]
Comparison

We compare the model with the converters reported in literature.

Proposed Model was close to 90% accurate.
Additional Energy Overheads

• Settling Time

\[ \Delta T = \frac{T}{V} \Delta V \]

Where \( T \) is the settling time of the converter when output voltage is charged to \( V \) from ground.

• Rail Switching Energy: Charging and discharging \( CL \) entails loss, when \( Vo \) changes to \( V1 \) from \( V2 \)

\[ Ec = Vin \cdot CL \cdot \{ \max(V1-V2,0) \} \]

Work is not done by \( Vi \) when \( V1 \) is lower than \( V2 \).
Outline

- Model of DC-DC converter
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Framework to calculate Energy cost

- Total Energy is broken down into two components, operating cost and conversion cost.

**Operating cost:**
\[
E_{op} = V_1 i_1 (T_1 + \Delta T_1)/\eta_1 + V_2 i_2 (T_2 + \Delta T_2)/\eta_2 + \ldots
\]

**Conversion cost:**
\[
E_c = V_{in} CL \{(\max(V_1 - V_2, 0) + \max(V_2 - V_3, 0)) \ldots\}
\]

**Total Energy:**
\[
E_{op} + E_c
\]
Outline

- Model of DC-DC converter
- Framework to obtain energy cost
- **Block level Power Management Techniques**
- Results
Block Level DVFS

- Idealized implementation to study the benefits of DVFS at block level.
- Each block has a dedicated VDD and implements its own DVFS.
- Each block is implemented as chain of inverters with different depth.
Block Level DVFS

For each block a table for operating condition can be obtained as shown, illustrating load and output voltages etc.

Energy overhead can be obtained as

\[ E_{op} = V_1 i_1 (T_1 + \Delta T_1)/\eta_1 + V_2 i_2 (T_2 + \Delta T_2)/\eta_2 + \ldots \]

\[ E_{op} \]

is the operating energy and \( \eta \) is calculated using (iii)

\[ E_c = V_{in} CL \{ (\max(V_1 - V_2, 0) + \max(V_2 - V_3, 0)) \ldots \} \]

Total Energy = \( E_{op} + E_c \).

<table>
<thead>
<tr>
<th>VDD</th>
<th>Load</th>
<th>Time of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 V</td>
<td>i1 uA</td>
<td>T1+\Delta T1 uS</td>
</tr>
<tr>
<td>V2 V</td>
<td>i2 uA</td>
<td>T2+\Delta T2 uS</td>
</tr>
<tr>
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<td></td>
<td>..</td>
</tr>
</tbody>
</table>

Optimal condition for a block

Example Table

<table>
<thead>
<tr>
<th>VDD</th>
<th>Load</th>
<th>Time of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 V</td>
<td>100uA</td>
<td>6+2 uS</td>
</tr>
<tr>
<td>1.2 V</td>
<td>900uA</td>
<td>5+3 uS</td>
</tr>
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<td>..</td>
</tr>
</tbody>
</table>
Comparison

We compare the model with the case where no power Management is implemented using the model.

- Figure shows that no energy benefits can be realized if rail switches at faster rate than 1μs.
- >2.5x energy benefits can be realized using DVFS
• Panoptic Dynamic Voltage scaling has been used to implement block level DVFS [3].
• In PDVS a block can dither between two rails to obtain an ideal operating condition
• It does not require rail to change and saves overheads
PDVS Operating Condition

<table>
<thead>
<tr>
<th>VDD</th>
<th>Load</th>
<th>$T_{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4V</td>
<td>0.8V</td>
</tr>
<tr>
<td>V1V</td>
<td>i11 uA</td>
<td>0</td>
</tr>
<tr>
<td>V1V</td>
<td>0</td>
<td>i12 uA</td>
</tr>
<tr>
<td>V2V</td>
<td>0</td>
<td>i21 uA</td>
</tr>
<tr>
<td>V2V</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>....</td>
<td></td>
</tr>
</tbody>
</table>

- Operating table for each block is broken down in PDVS, like shown above
- On each power supply we get the following condition,

$$E_{op} = 0.4 \int i_1(t)/\eta_1(i1) \, dt + 0.8 \int i_2(t)/\eta_2(i2) \, dt + 1.2 \int i_3(t)/\eta_2(i2) \, dt$$
Result

We compare PDVS with block level DVFS using the model.

PDVS can start realizing energy benefits at VDD switching time of 10ns, however maximum energy benefit is lower because PDVS sees wider load variation.
Conclusion

• A power model which can accurately predict the behavior of DC-DC converter in a dynamic environment has been presented.

• The model has been validated and compared with existing literature.

• We use this model to study block level power management techniques for an SOC, ex PDVS.

• The model predicts that there is a break-even time, before the benefit of voltage scaling becomes positive.
Acknowledgement

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References