Prototype Implementation of a High Efficiency, Soft Switching DC-DC Converter with Adaptive Current-Ripple Control

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Motivation

- **Motivation for Improving Efficiency in Mobile Applications**

  - **Portable application ➡ Compact, low power, low cost, SOC**

  - **Process technology advancement**
    Single battery operation } ➡ **Low voltage circuits**

  - **Extension of battery life ➡ Highly power efficient DC-DC converter**

- **Research Goal**

  Improve ***power efficiency*** of integrated DC-DC converters to ***extend battery life*** for ***portable, battery-powered*** applications.

Evaluation of Battery Life

- **Battery Life**

$$\text{Battery Life [h]} = \frac{\text{Battery Capacity [mAh]}}{\text{Total Average (Weighted) Battery Current [mA]}}$$

- **Total Average (Weighted) Battery Current, $I_{Batt\_Avg\_Tot}$**

$$\eta(I_{load}) = \frac{V_{out} \times I_{load}}{V_{Batt} \times I_{Batt}} \quad \Rightarrow \quad I_{Batt}(I_{load}) = \left(\frac{V_{out}}{V_{Batt}}\right)\frac{I_{load}}{\eta(I_{load})}$$

$$I_{Batt\_Avg\_Tot} = \int_0^{I_{load\_max}} \left[PDF(I_{load}) \times I_{Batt}(I_{load})\right] dI_{load} = \sum_i \underbrace{Probability(I_{load}) \times I_{Batt}(I_{load})}_{\text{Charge (Energy) drawn from the battery}}$$

Charge (Energy) drawn from the battery

- **Conclusion**
  - **Battery life is highly dependent on the probability distribution (PDF) of the load.**
  - **Improve power efficiency at the load current where the most charge / energy is drawn from the battery, i.e., ($Probability \times I_{Batt}$) is the largest.**

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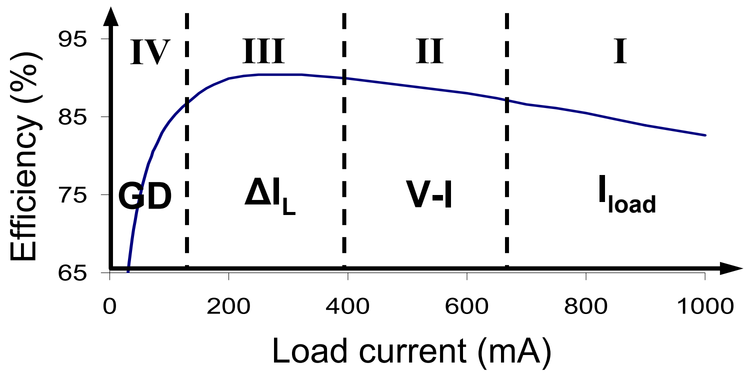
Adaptive Current Ripple Control

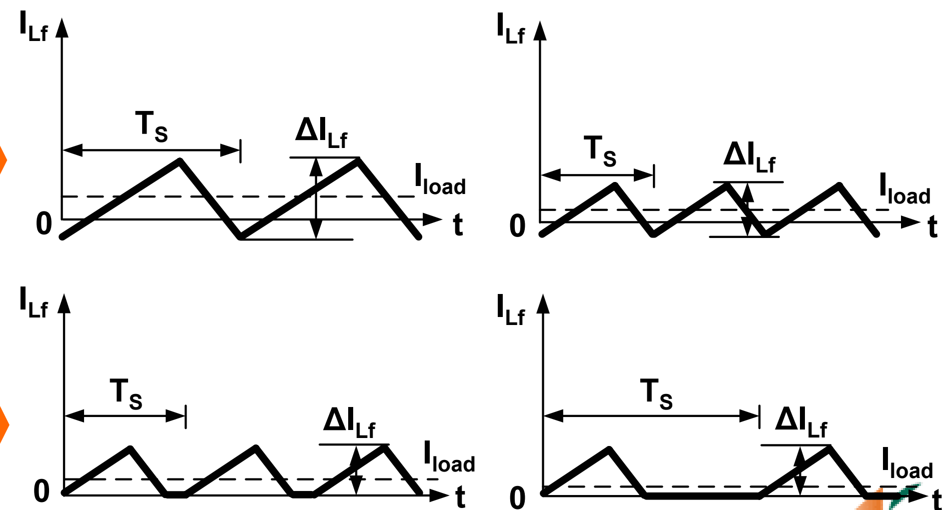
- Idea



Soft switching + **Reduce current ripple**

to optimize the efficiency !

- Operation Modes
  - **High loads (region I): Constant current ripple, hard switching**
  - **Moderate and light loads (region II & III): Adaptive ripple, Soft switching**
  - **Very light loads (region IV): Constant peak current, hard switching (Burst Mode)**



Effect of Power MOSFET Size

• **Characteristics of Power MOSFET**

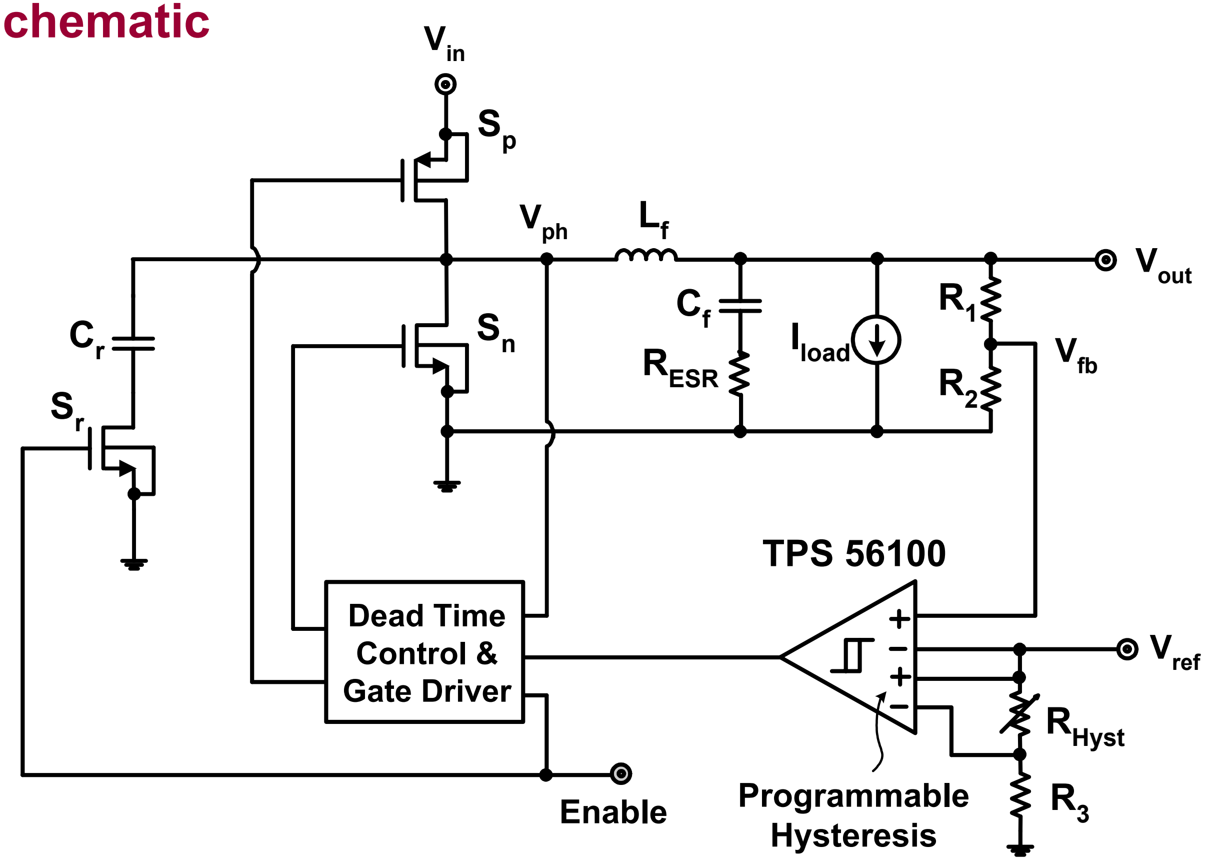
	ON-Resistance Conduction Loss	Input Capacitance Switching Loss
Big FET (e.g. IRF 7309)	Small (e.g. 80 mΩ at 4.5V)	Big (e.g. 520 pF)
Small FET (e.g. IRF 7105)	Big (e.g. 160 mΩ at 4.5V)	Small (e.g. 330 pF)

• **Conclusions**

- At *high loads* ➡ Conduction losses dominate ➡ Use *big FET*
- At *light loads* ➡ Switching losses dominate ➡ Use *small FET*
- If power MOSFETs are integrated ➡ *Dynamic Gate Sizing*

Prototype Implementation

- **Top Level Schematic**



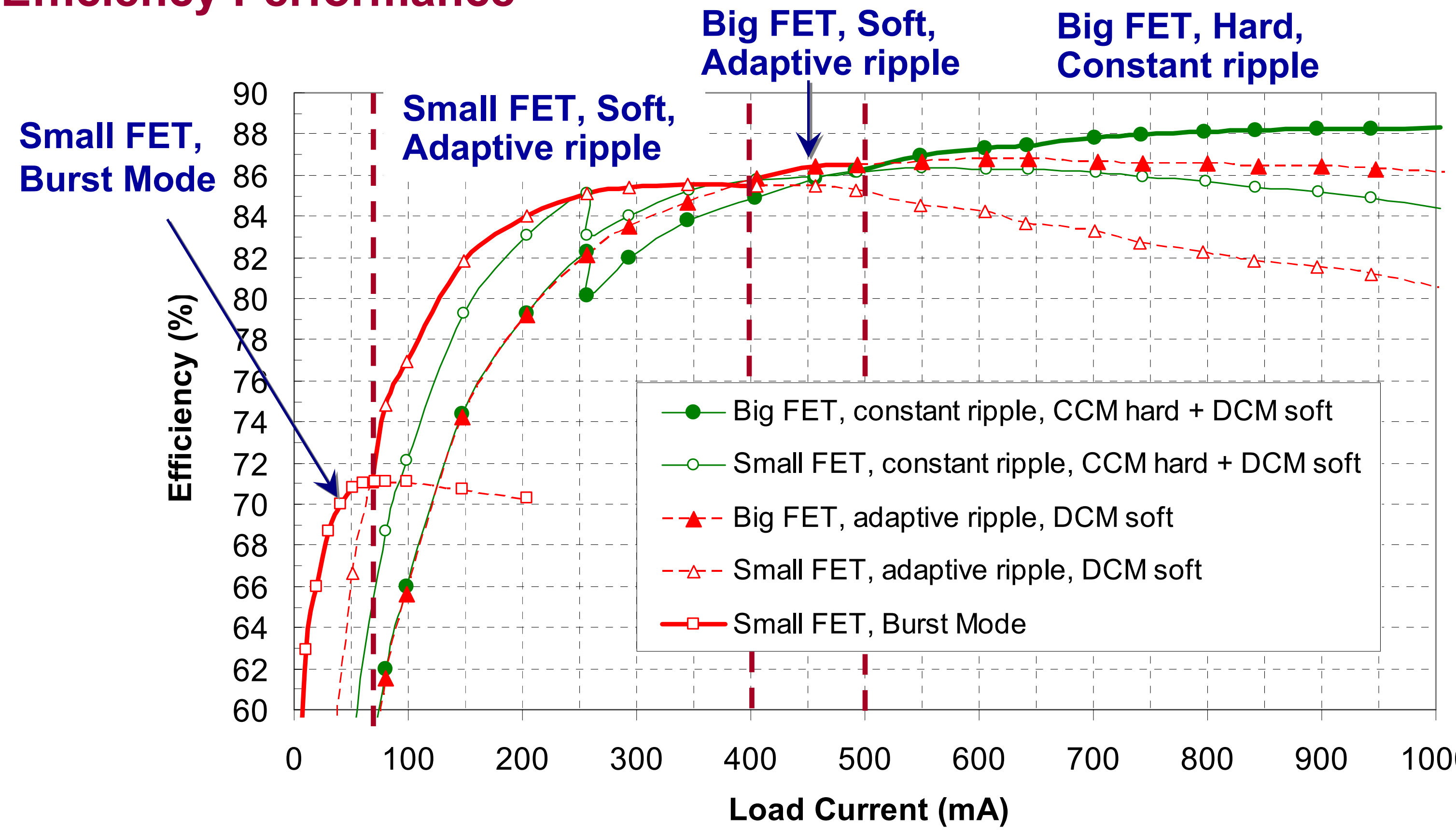
- **Comments**
  - Assuming output voltage is ESR dominant, voltage-mode hysteretic control is used to adaptively regulate the inductor current ripple.
  - Hysteresis is manually adjusted for the minimum current ripple needed for soft switching.

Experimental Results – Power Efficiency

- **Converter Parameters**

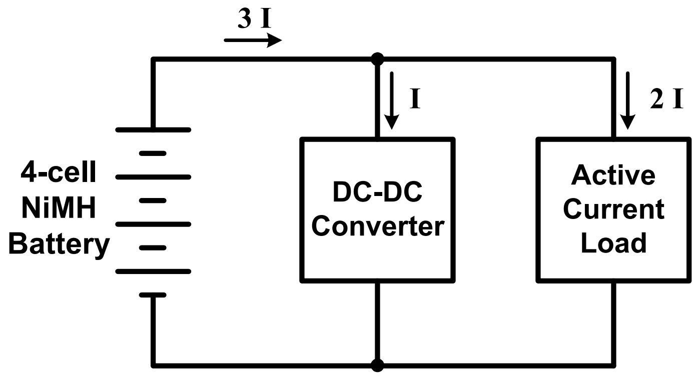
V_{in} = 5V, V_{out} = 1.8V, 0 < I_{load} < 1A
L_f = 8.2 μH (20 mΩ ESR), C_f = 47 μF (75 mΩ ESR), C_r = 4.5 nF

- **Efficiency Performance**



Experimental Results – Battery Life

- **Stress Test Setup**



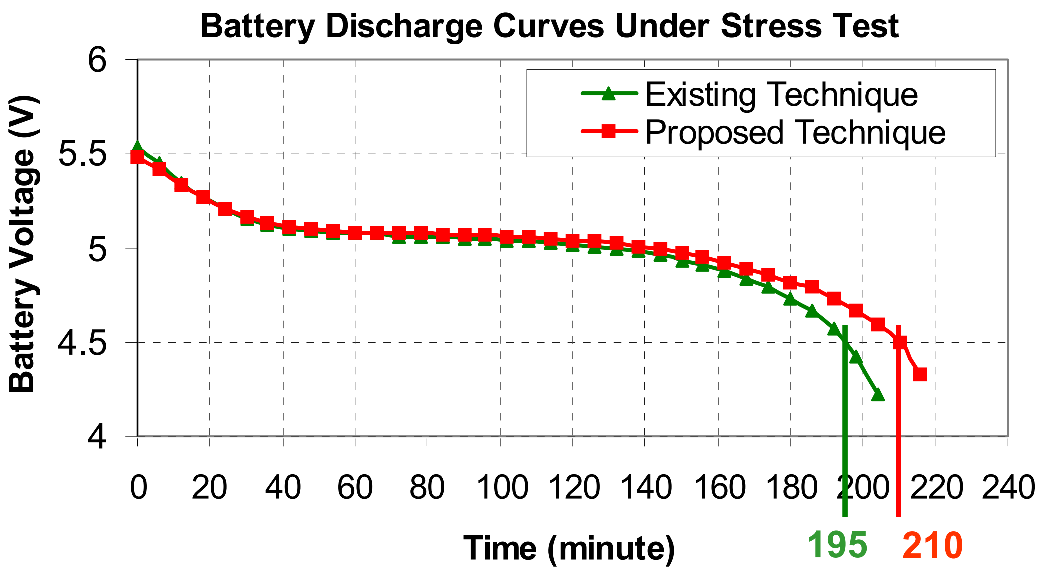
- **Load Probability**

For DSP, μProcessor Application

I_{load} (mA)	0.1	1	10	100	300
Prob (%)	90	4	3	2.5	0.5
Product	9	4	30	250	150

Improve efficiency at 100 mA, not 100 μA, to prolong battery life !

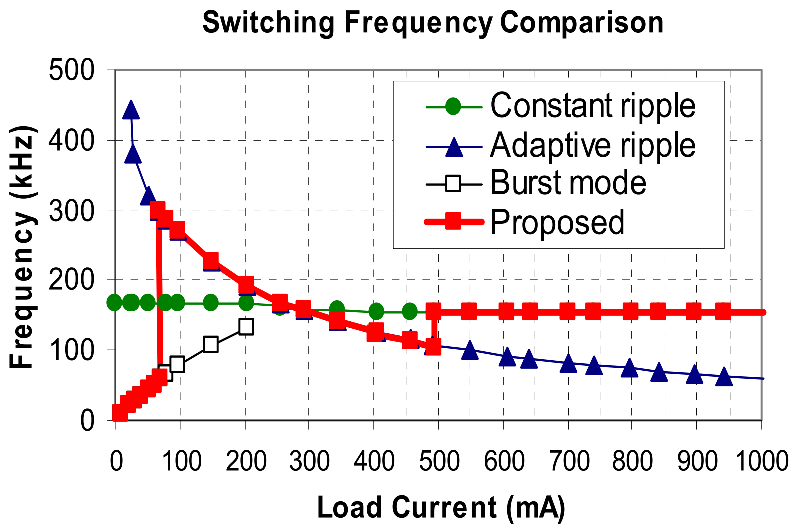
- **Results**

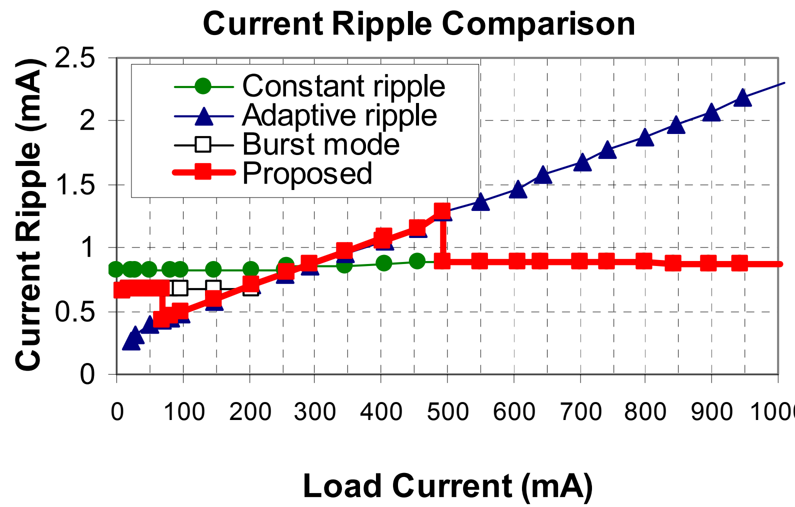


6 % improvement in battery life

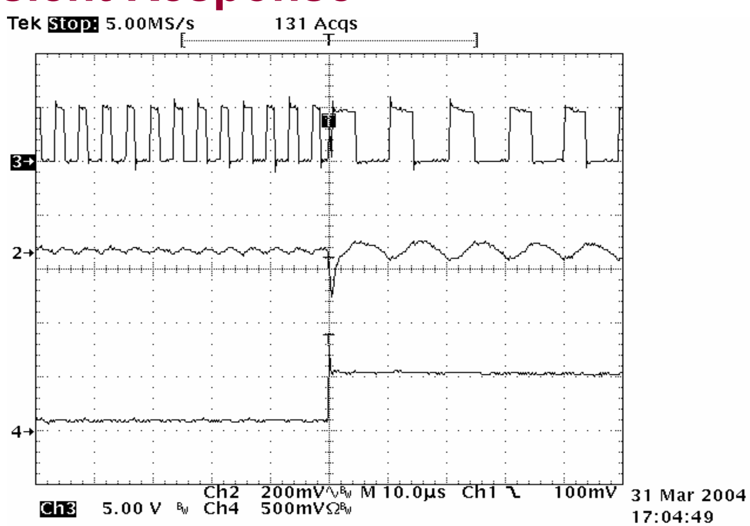
Experimental Results – Other Performance

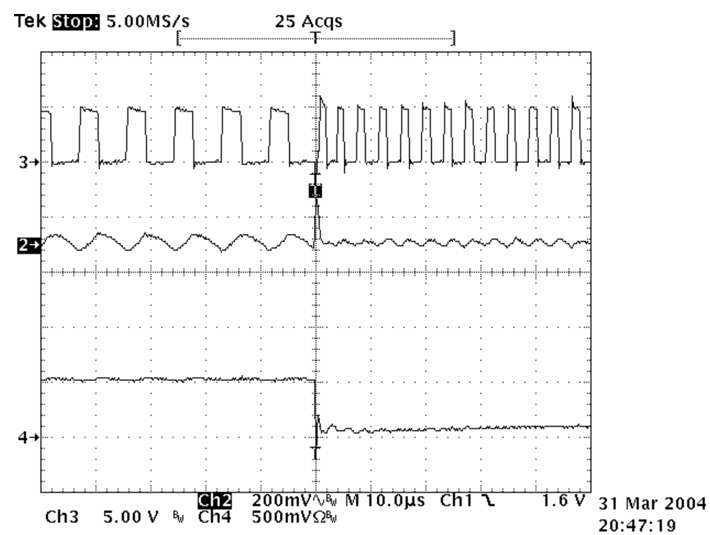
- **Switching Frequency and Current Ripple**





- **Transient Response**





Conclusion and Future Work

- **Conclusion:**
  - Improve the power efficiency at the load current where the most charge / energy is drawn from the battery, which may not be the highest probability load.
  - Adaptive current ripple control in DCM soft switching improves the power efficiency at light and moderate load currents, which significantly increases the battery life.
  - Using small power MOSFET at light loads further reduces the switching loss, therefore dynamic gate sizing is beneficial in the integrated solution.
- **Future Work:**
  - Investigate how to sense the load current to automatically adjust the hysteresis.
  - Investigate how to determine the mode transition points automatically.
  - Investigate how to implement the control strategy with ceramic output capacitors.
  - Implement the whole system in an integrated circuit.