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
  - Portable devices operate in stand-by mode most of the time ➡ Light-load efficiency is crucial for extending battery life
- **Research Goal**

  Improve ***power efficiency***, especially at ***light loads***, of integrated DC-DC converters 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, $I_{Batt\_Avg\_Tot}$**

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

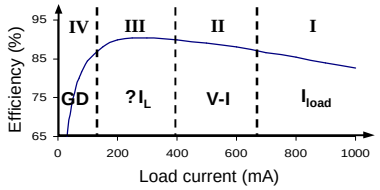
$$I_{Batt\_Avg\_Tot} = \int_0^{I_{load\_max}} [PDF(I_{load}) \times I_{Batt}(I_{load})]\, dI_{load} = \left(\frac{V_{out}}{V_{Batt}} \div \int_0^{I_{load\_max}} \left[\frac{PDF(I_{load}) \times I_{load}}{?(I_{load})}\right] dI_{load} \quad \textbf{(continuous)}$$

$$= \sum_i Probability(i) \times I_{Batt}(i) = \left(\frac{V_{out}}{V_{Batt}} \div \sum_i \left[\frac{Probability(i) \times I_{load}(i)}{?(i)}\right] \quad \textbf{(discrete)}$$

- **Conclusion**
  - **Battery life is highly dependent on the probability distribution (PDF) of the load.**
  - **Improve power efficiency at the load current where PDF×I_{load} is the largest.**

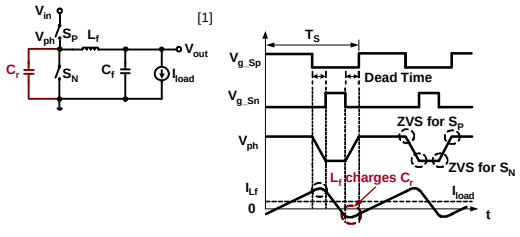
Adaptive Current Ripple Control

- Partition of Efficiency Curve



Soft switching + Reduce current ripple to optimize power efficiency !

- Soft Switching Technique - Turn on/off MOS switches when V_{ds} = 0 or I_{ds} = 0

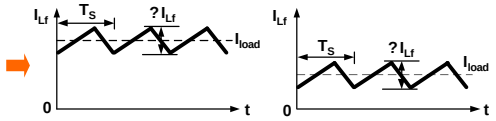


- ***Advantage:***
  - Only 1 additional off-chip component
  - Quasi Square Wave (QSW) operation
- ***Disadvantage:***
  - Excess, constant current ripple conduction losses degrade light-load efficiency
- ***Conclusion:***
  - Adaptively reduce ripple while ensuring ZVS at light loads is the best !

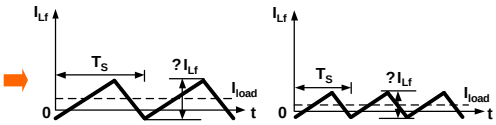
[1] A.J. Stratakos, S.R. Sanders and R. Brodersen, "A Low-Voltage CMOS DC-DC Converter for a Portable Battery-Operated System," *25th Annual IEEE Power Electronics Specialists Conference*, Vol. 1, 1994, pp. 619–626.

Proposed Control Strategy

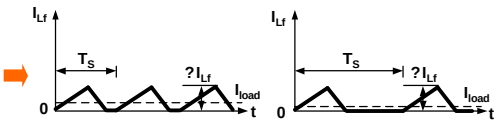
- Operation Modes
  - **High Loads (Region I):**
    - **Hard switching**
    - **Constant current ripple**



  - **Moderate and Light Loads (Region II & III):**
    - **Soft switching**
    - **Adaptive current ripple**

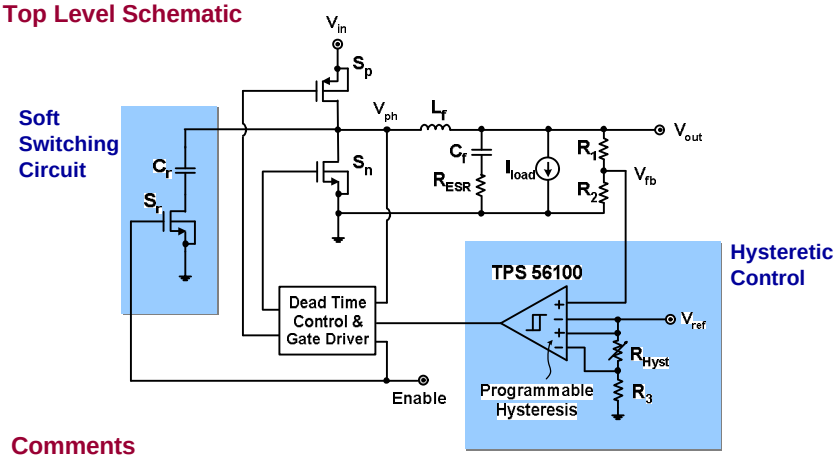


  - **Very Light Loads (Region IV):**
    - **Hard switching**
    - **Constant peak current**
    - **DCM (Skip Mode)**



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.

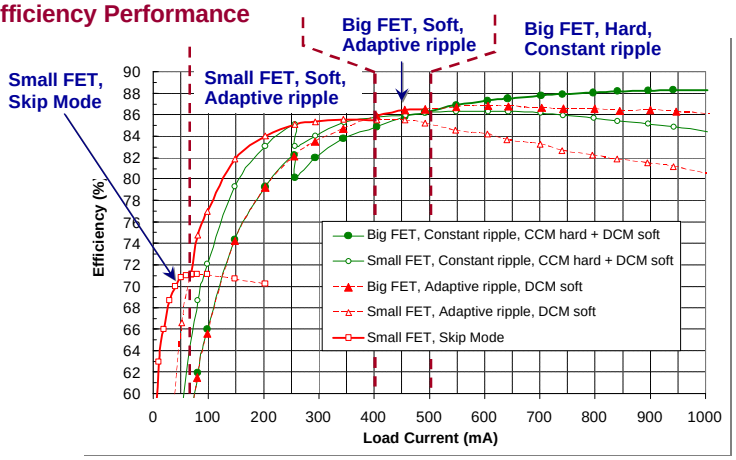
Experimental Results – Power Efficiency

- **Converter Parameters**

  V_{in} = 5V, V_{out} = 1.8V, 0 < I_{load} < 1A

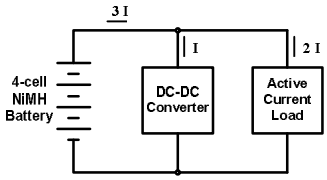
  L_f = 8.2 µH (20 m? ESR), C_f = 47 µF (75 m? ESR), C_r = 4.5 nF

- **Efficiency Performance**



Experimental Results – Battery Life

- **Stress Test Setup**



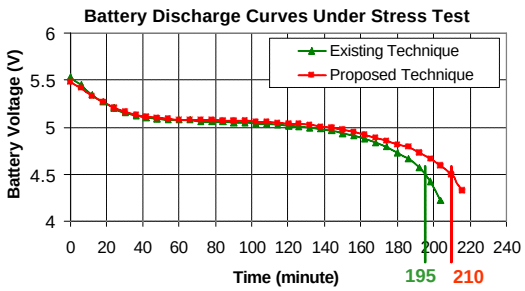
- **Load Probability**

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 100mA!

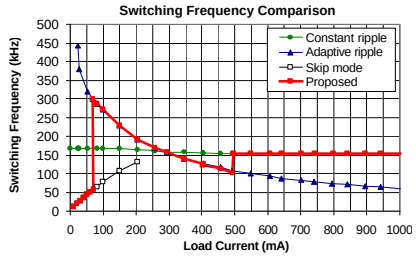
- **Test Results**

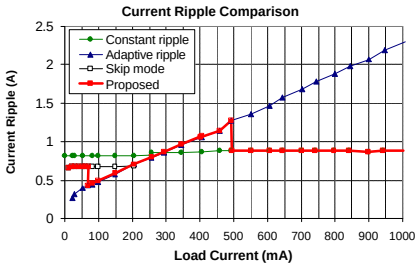


➡ 6.6 % improvement in battery life

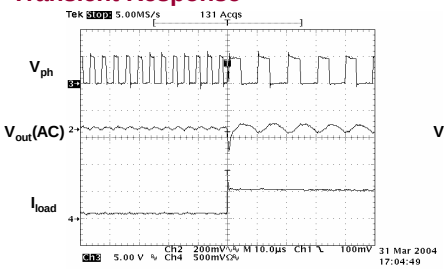
Experimental Results – Other Performance

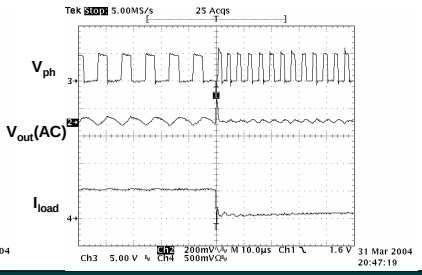
- **Switching Frequency and Current Ripple**





- **Transient Response**





Conclusion and Future Work

- **Conclusion:**
  - **Adaptive current ripple in DCM soft switching improves the power efficiency at light load currents.**
  - **Using small power MOSFETs at light loads further reduces the switching loss, therefore dynamic gate sizing is beneficial in the integrated solution.**
  - **Battery Life Improvement is dependent on the product of probability distribution of load current and the load current itself.**
- **Future Work:**
  - **Investigate how to control the current ripple automatically w.r.t. the load current.**
  - **Investigate how to determine the mode transition points automatically.**
  - **Investigate how to implement the control strategy with ceramic output capacitors.**
  - **Implement the whole system on an integrated circuit.**