A High Efficiency, Soft Switching DC-DC Converter with Adaptive Current Ripple Control for Mobile, Battery-Powered Applications

GTAC Research Review

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Abstract

- **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.

- **Background: power losses**
  - Conduction losses
    - Load current (DC) loss
    - Current ripple (AC) loss
  - Switching losses
    - V-I overlap loss
    - Gate-drive loss
Classification of Power Losses

- **Partition of Efficiency Curves**

  - **Current Ripple:** systematic, steady-state (large) ripple

- **Conclusions**
  - For region I: Synchronous mode is the best
  - For region II: *Soft switching* or decrease the frequency is the best
  - For region III: *Reduce the current ripple* is the best
  - For region IV: Decrease the frequency is the best

  ![Efficiency Curves](image)

  ![Power Loss Curves](image)

  ➡️ *Soft switching* + *Reduce current ripple* to optimize the efficiency!
Existing Soft Switching Techniques

- **Soft switching**: Turn on/off MOS switches when $V_{ds} = 0$ or $I_{ds} = 0$

- **Option 1: CCM (ZVT)**

  ![Diagram of CCM (ZVT)]

  - **Advantage**: Small current ripple in $L_f$, good accuracy
  - **Disadvantage**:
    - Diode: voltage drop and more losses
    - Fixed losses in $S$, $D$, $L_r$, $C_r$ degrade light-load efficiency
  - **Conclusion**: Not suitable for low voltage and light loads

- **Option 2: Synchronous DCM (QSW)**

  ![Diagram of Synchronous DCM (QSW)]

  - **Advantage**: Only 1 additional off-chip component, 1 cell
  - **Disadvantage**: Large and constant current ripple losses
  - **Conclusion**: Suitable for light loads, but needs modification

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Proposed Technique - Control Strategy

- **Idea:**
  - Soft switching over wide load range while adaptively controlling current ripple
  - Mode hopping to the most efficient mode depending on the load current

- **Control Strategy:**
  - **Mode 1** (high and moderate loads):
    - Soft switching in CCM
    - Minimum current ripple
    - Highest \( f_S \) (e.g. 2 MHz)

  - **Mode 2** (light loads):
    - Soft switching in synchronous DCM
    - Current ripple proportional to \( I_{load} \)
    - \( f_S \) is first lowered (e.g. 430 kHz), then
      - \( f_S \uparrow \) with \( I_{load} \downarrow \) (e.g. 430 kHz to 1 MHz)

  - **Mode 3** (very light loads): [1]
    - Hard switching in asynchronous DCM
    - Constant current ripple (constant \( t_{on} \))
    - \( f_S \downarrow \) with \( I_{load} \downarrow \), \( \eta \neq f(I_{load}) \)

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• **Assumption:** Output voltage ripple is dominated by the ESR of the filter capacitor

• **Hysteretic Control – Why?**
  - Simple topology, low cost
  - Inherently stable (no compensation)
  - Fast transient response
  - Programmable hysteresis \((V_{\text{hyst}})\)
  - Self oscillating, \(f_S = f(V_{\text{hyst}})\)

• **The User-Programmable Hysteretic Comparator**

\[
\Delta I_L = \frac{\Delta V_{\text{out}}}{R_{Cf_{ESR}}} = \frac{V_{\text{hyst(U)}} + V_{\text{hyst(L)}}}{R_{Cf_{ESR}}}
\]

- Asymmetrical hysteresis is set to control **asynchronous DCM (Mode 3)**

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Proposed Technique - Implementation

• Circuit Diagram

• Comments
  - Adaptively program (reduce) the hysteresis of comparator 1 in Mode 2 as $I_{load}$ decreases
  - No diode used for ZVS in CCM (Mode 1) ➔ Need precise zero-crossing detection circuit
Proposed Technique - Implementation

• Detailed Waveforms of the Proposed Converter

**Mode 1**
- $V_1 = "1", \text{ connect } L_r$
- $V_2 = "1", \text{ connect } C_r$

**Mode 2**
- $V_1 = "0", \text{ disconnect } L_r$
- $V_2 = "1", \text{ connect } C_r$

**Mode 3**
- $V_1 = "0", \text{ disconnect } L_r$
- $V_2 = "0", \text{ disconnect } C_r$

\[ V_{11(U)} = V_{11(L)} = 2 \]  
\[ V_{21(U)} = V_{21(L)} \]  
\[ \Delta I_{Lf} = \text{minimum and constant} \]

\[ V_{12(U)} = V_{12(L)} = 1.25 \times R_{Cf\_ESR} \times I_{load} \]
\[ \Delta I_{Lf} = 2.5 \times I_{load} \]

\[ V_{13(U)} > V_{13(L)} = f(I_{pk}, ESR, L_p, C_p, V_{inv}, V_{out}) \]
\[ \Delta I_{Lf} = I_{pk} = \text{preset and constant} \]
Simulation Results

\[ V_{in} = 2.4V, V_{out} = 1.2V; \quad L_f = 2\mu H, C_f = 47\mu F, L_r = 150nH, C_r = 10nF; \]
\[ R_{ON \_Sp} = 200m\Omega, R_{ON \_Sn} = R_{ON \_S1} = R_{ON \_S2} = 80m\Omega, R_{L\_ESR} = 10m\Omega, R_{C\_ESR} = 75m\Omega; \]

“Best reported”:
Combination of [1] to [4]

- **Switching Frequency**

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**Efficiency of the buck converter**

- Mode 1: 3% improvement
- Mode 2: 4% improvement
- Mode 3: 4% improvement

**Estimated Battery Life Improvement**

\[
\eta_{avg} = \frac{1}{P_{out_{max}}} \int_0^{P_{out_{max}}} P_{out} \times \text{Prob}(P_{out}) dP_{out}
\]

\[
\int_0^{P_{out_{max}}} P_{in}(P_{out}) \times \text{Prob}(P_{out}) dP_{out}
\]

3% improvement in battery life for CDMA cell phone application

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[1] Synchronous CCM, \( f_s = 500kHz \)
[4] B. Arbetter 1995, Asynchronous DCM, constant on time, variable \( f_s \)
Conclusion and Future Work

**Advantages:**
- At high/moderate loads (*Mode 1*): soft switching in CCM, minimum $\Delta I_{Lf}$
- At light loads (*Mode 2*): soft switching in synchronous DCM, $\Delta I_{Lf}$ proportional to $I_{load}$
- At very light loads (*Mode 3*): constant $\Delta I_{Lf}$ in asynchronous DCM, so $\eta \neq f(I_{load})$
- Use hysteretic control in all three modes: simple, fast, and adaptive

**Disadvantages and Problems:**
- Variable frequency leads to EMI problem. But at light loads, the power is small and spread.
- For very small filter capacitor ESR (ceramic capacitor), $\Delta I_{Lf}$ and $\Delta V_{out}$ are orthogonal.
- Internal delay and resonance at light loads make the actual ripple larger than designed.

**Conclusion:**
- The proposed control strategy significantly improves *light-load efficiency* of DC-DC converters by adaptively controlling the current ripple.
- The proposed circuit implementation is suitable for *low voltage* DC-DC converters in *portable, battery-powered applications*.

**Future Work:** Prove the concept by prototyping on a PCB and integrated circuit.