A New Digital Control Algorithm to Achieve Optimal Dynamic Performance in DC-to-DC Converters

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Presentation Overview

1. ***Introduction***
2. **Limitations of Conventional Control Methods During a Load Transient**
3. **Proposed Optimal Transient Response Algorithm**
4. **Derivation of the Optimal Control Algorithm for Practical Implementation**
5. **Experimental Results**
6. **Conclusions**

1. Introduction

- **Increasing demand for dynamic performance including:**
  - **Minimum output voltage overshoot/undershoot**
  - **Minimum output voltage recovery time**
- **Output voltage deviates under line or load changes**
- **Different control algorithms achieve different dynamic performance**

Introduction Continued …

- **In theory there exists a best possible dynamic performance**
  - **Minimum overshoot and/or recovery time**
- **KEY: determine best possible dynamic response and a method to realize it!**
- **Paper proposes an optimal control algorithm using principle of capacitor charge balance**
  - **Algorithm implemented digitally using an FPGA**

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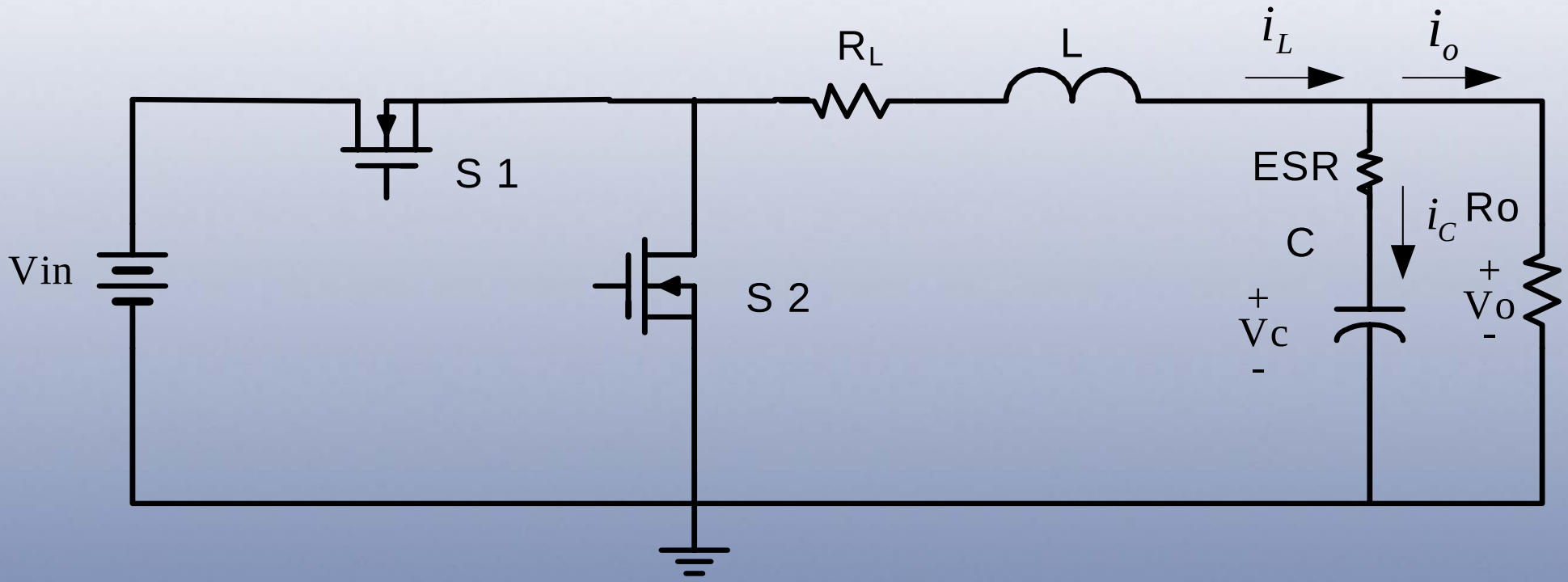
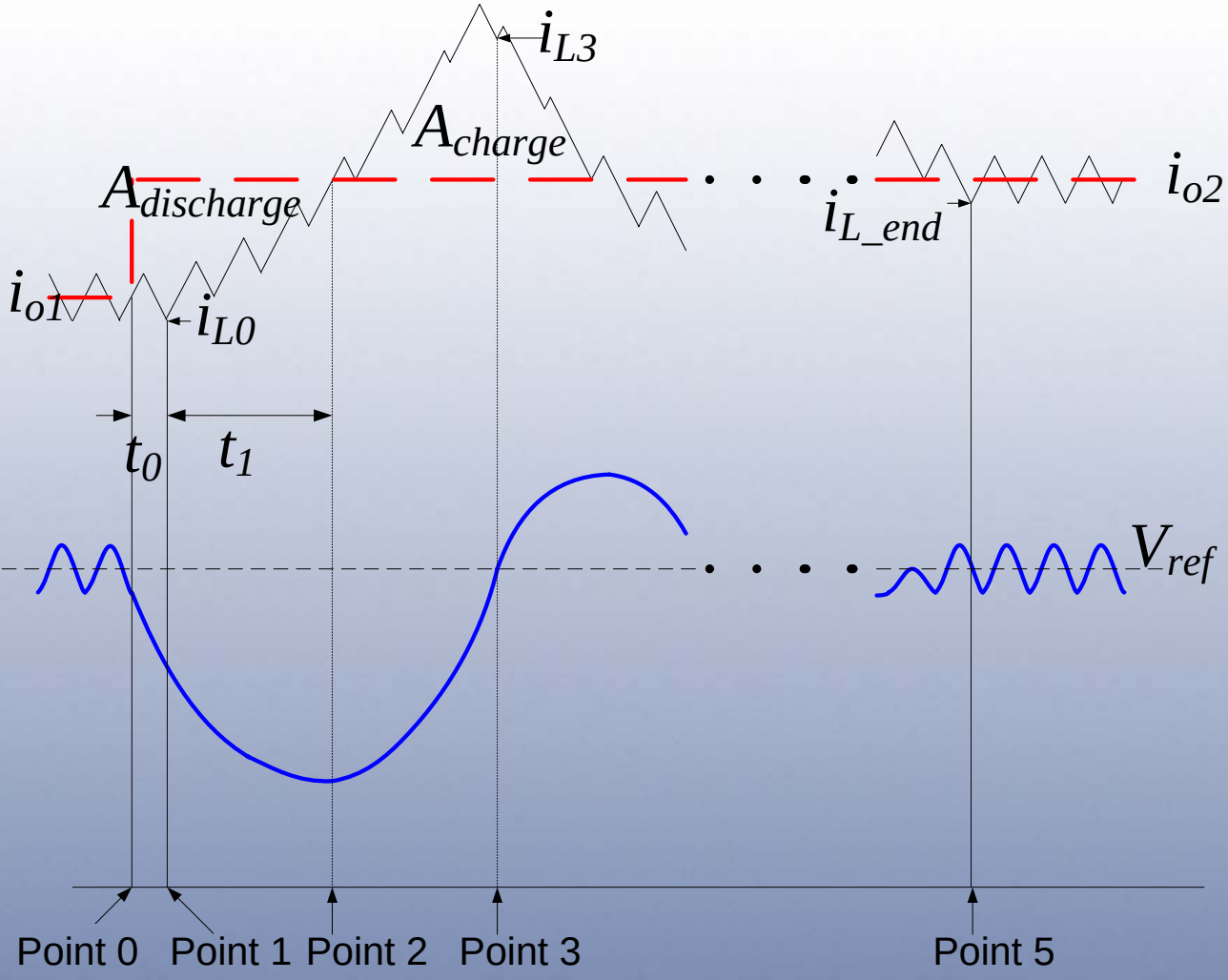
2. Limitations of Conventional Control Methods During a Load Transient

e.g. Buck converter under voltage mode control



Voltage Mode Controlled Buck: Positive Load Current Step



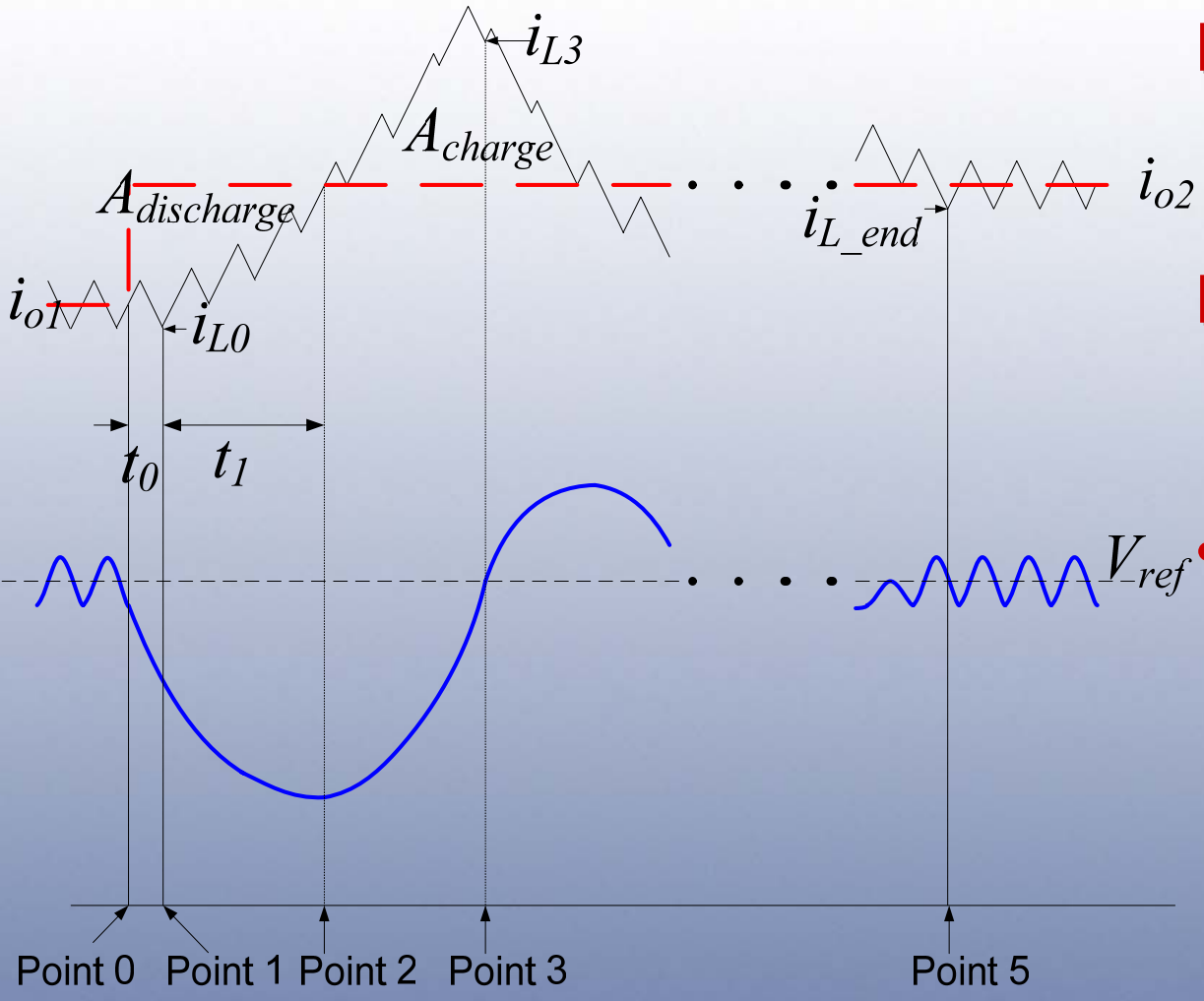
Point 0:

1. Load steps
2. Output not sensed yet
3. I_L unchanged
4. Capacitor discharges

Point 1:

1. Output drop sensed
2. D increases
3. I_L increases
4. But, I_L<Io
5. Capacitor continues to discharge

Voltage Mode Controlled Buck: Positive Load Current Step



Point 2:

1. **I_L=Io, cap drop is maximum**

Point 3:

1. **Transient continues to point 3 and beyond**

D never 100% !!!

- **Response not optimal**
- **similar response for other linear methods**

Voltage Mode Controlled Buck: Positive Load Current Step

DISADVANTAGE - D not 100% during t_1:

- **Inductor current does not increase at max possible slew rate**
- **t_1 is NOT minimized**
- **$A_{discharge}$ is not minimized**
- **Capacitor voltage drop is not minimized**

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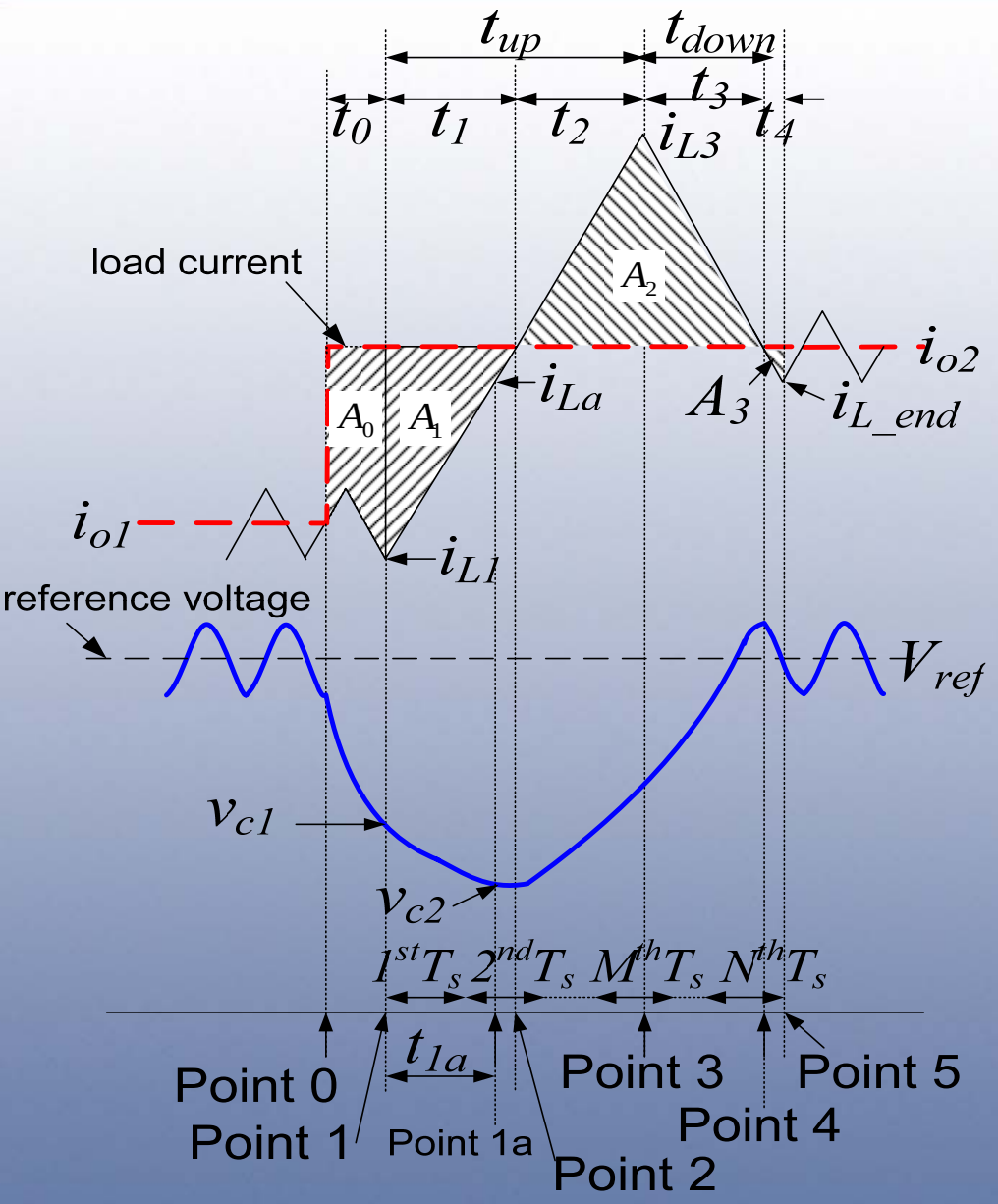
3. Proposed Optimal Transient Response Algorithm

Necessary and sufficient conditions for the best possible dynamic performance:

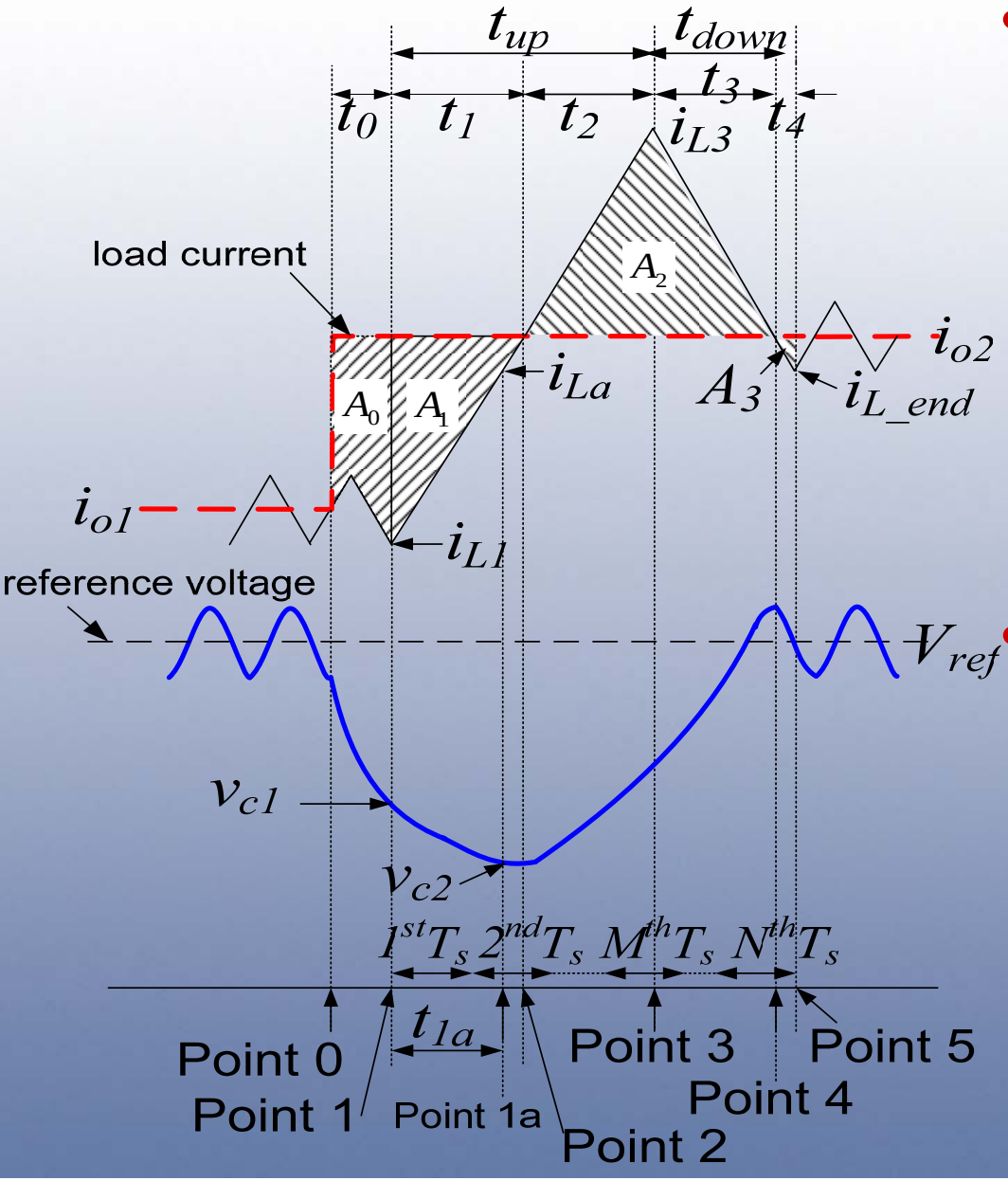
1. I_L rise at max slew rate at beginning of transient, then at the peak it should drop at max slew rate
2. Transient ends when capacitor charge balance is achieved
3. D set to new steady-state value at end of transient

Optimal Transient Response Algorithm Under Load Step



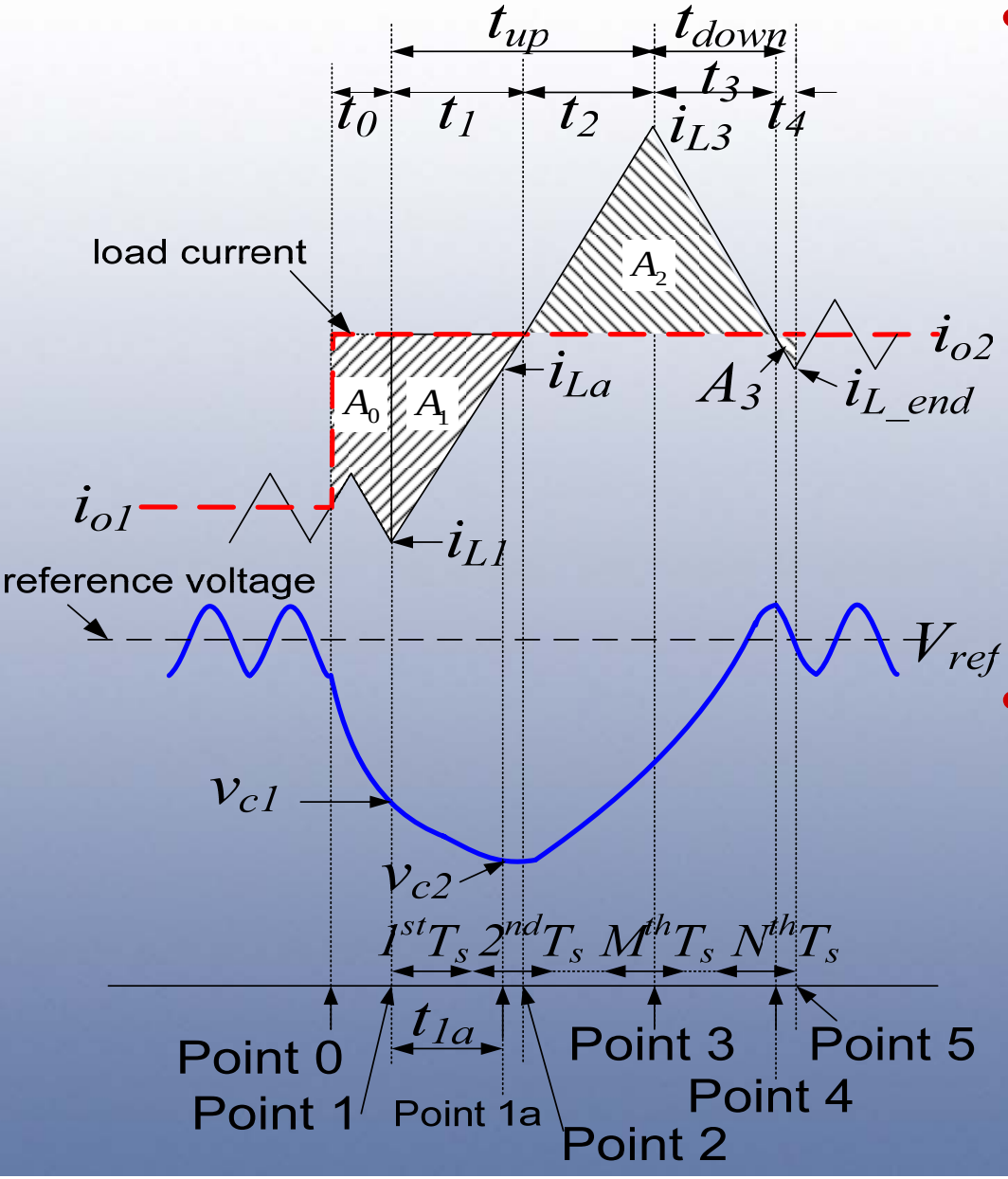
- **Point 0:**
  1. **Load steps**
  2. **Output not sensed yet**
  3. **I_L unchanged**
  4. **Capacitor discharges**
- **Point 1:**
  1. **Output drop sensed as large signal transient**
  2. **D=100%**
  3. **I_L increases at max slew rate**
  4. **But, I_L<Io**
  5. **Capacitor continues to discharge**
- **Point 2:**
  1. **I_L=Io,**
  2. **Capacitor drop is maximum**
  3. **D continues at 100%**

Optimal Transient Response Algorithm Under Load Step



- **Point 3:**
  1. **Inductor current reaches peak, I_{L3} using optimum t_{up}**
  2. **Inductor current then enters maximum down slope interval until point 4**
  3. **D=0%**
  4. **I_L>Io**
- **Point 4:**
  1. **I_L=Io**
  2. **D=0%**
  3. **I_L continues to decrease until end of switching cycle at point 5**

Optimal Transient Response Algorithm Under Load Step



- **Point 5:**
  1. **I_L reaches new steady-state value, i_{L_end}**
  2. **Charge delivered from capacitor = charge delivered to capacitor**
  3. **Large signal transient ends**
  4. **Conventional small-signal controller takes over**
- **KEY - need to determine:**
  - **Optimized up time, t_{up}**
  - **Optimized down time, t_{down}**

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4. Derivation of the Optimal Control Algorithm for Practical Implementation

- **Equations used for digital implementation**
- **Covered in more detail in the paper**
- **Six key steps after sensing large signal transient condition:**

1. **Sense large signal transient in output voltage, then apply maximum rising slew rate**

$$\frac{di_L}{dt} = \frac{v_{in} - v_o'}{L}$$

2. **Estimate new load, i_{o2}**

$$i_{o2} = \frac{1}{2}(i_{L1} + i_{La}) - \frac{C \cdot (v_{0a} - v_{o1}) - C \cdot (i_{La} - i_{L1}) \cdot ESR}{t_{1a}}$$

Derivation of the Optimal Control Algorithm for Practical Implementation

3. Calculate capacitor discharge portion A_0

$$A_0 = C \cdot (v_{C0} - v_{C1}) \approx C \cdot (V_{ref} - v_{C1}) = C \cdot (V_{ref} - v_{o1} + i_{C1} \cdot ESR)$$

$$= C \cdot (V_{ref} - v_{o1} + (i_{L1} - i_{o2}) \cdot ESR)$$

4. Calculate t_1 and discharge portion A_1

$$t_1 = \frac{i_{o2} - i_{L1}}{(v_{in} - v_o')/L} \qquad A_1 = \frac{1}{2} t_1 (i_{02} - i_{L1})$$

5. Calculate t_4 and discharge portion A_3

$$t_4 = \frac{i_{o2} - i_{L\_end}}{v_o'/L} \qquad A_3 = \frac{1}{2} t_4 \cdot (i_{02} - i_{L\_end})$$

6. Calculate charge A_2 and time periods t_2 and t_3

$$A_2 = \frac{1}{2}(t_2 + t_3) \cdot (i_{L3} - i_{02}) \qquad t_2 = \sqrt{\frac{A_0 + A_1 + A_3}{\frac{1}{2}\frac{v_{in}}{v_o'}\frac{v_{in} - v_o'}{L}}} \qquad t_3 = \frac{v_{in} - v_o'}{v_o'} t_2$$

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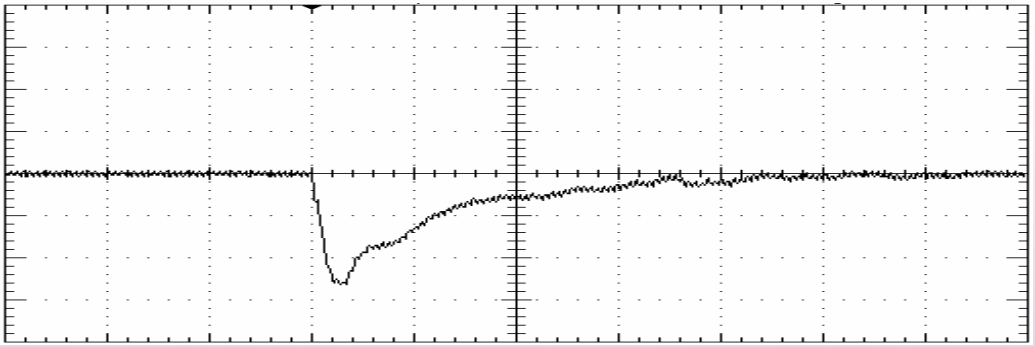
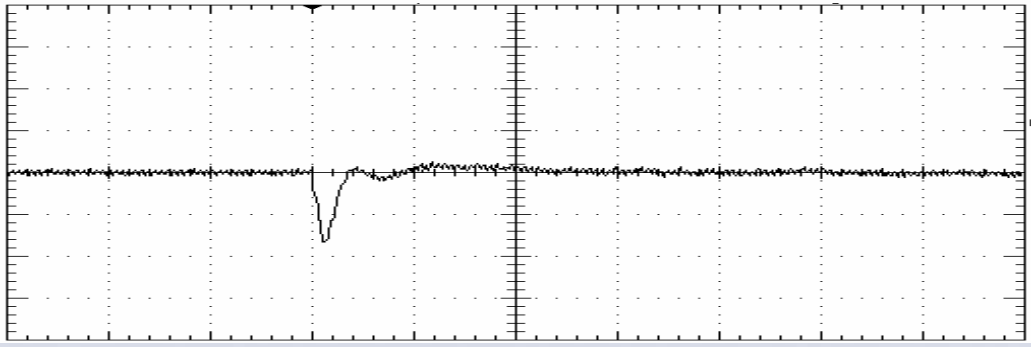
5. Experimental Results

- **FPGA was used to implement the proposed optimal control algorithm with a synchronous buck converter**
- **Buck Parameters:**
  - ***Vin=5V***
  - ***Vo=2.5V***
  - **load power=25 W**
  - ***L=1μH*,**
  - ***C=235μF***
  - **ESR=1mΩ**
  - **R_L=2mΩ**
  - ***fs*=400khz**

Output Voltage Response to Load Step from 0A to 5A



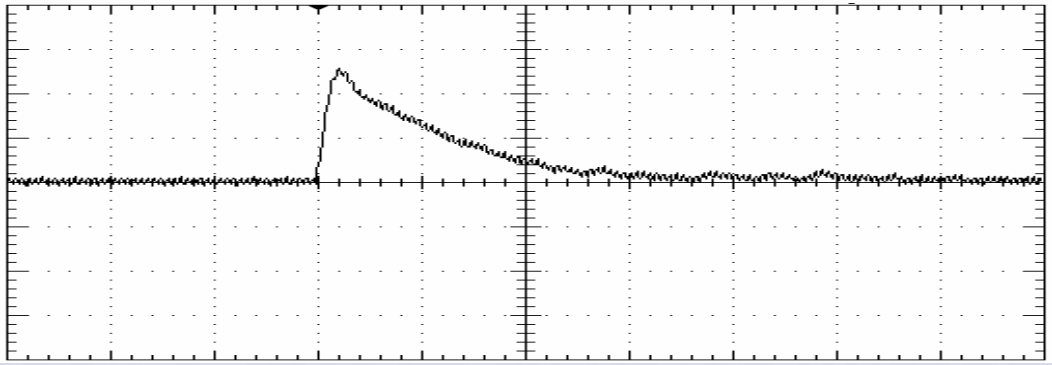
(a) Current mode PID controller



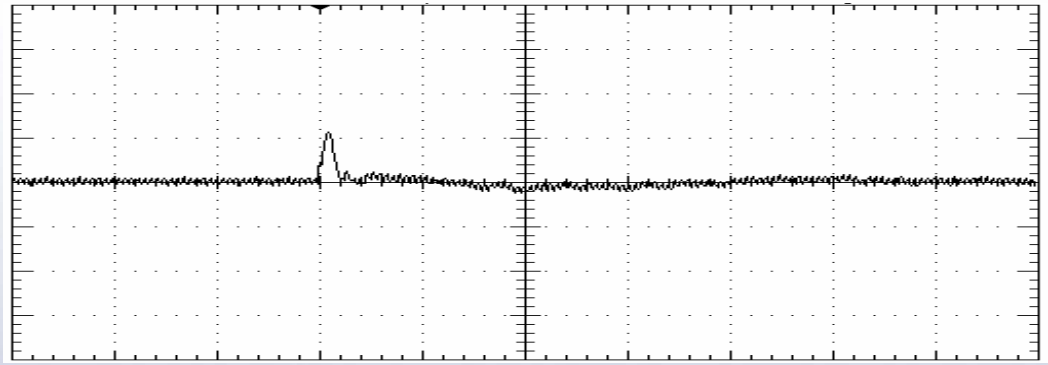
(b) Proposed optimal control algorithm

(X axis: 40us/div; Y axis: 50mv/div)

Output Voltage Response to Load Step from 5A to 0A



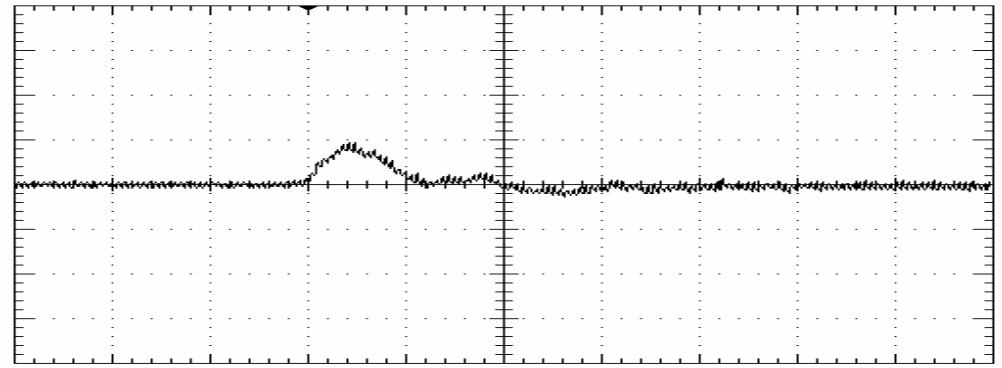
(a) Current mode PID controller



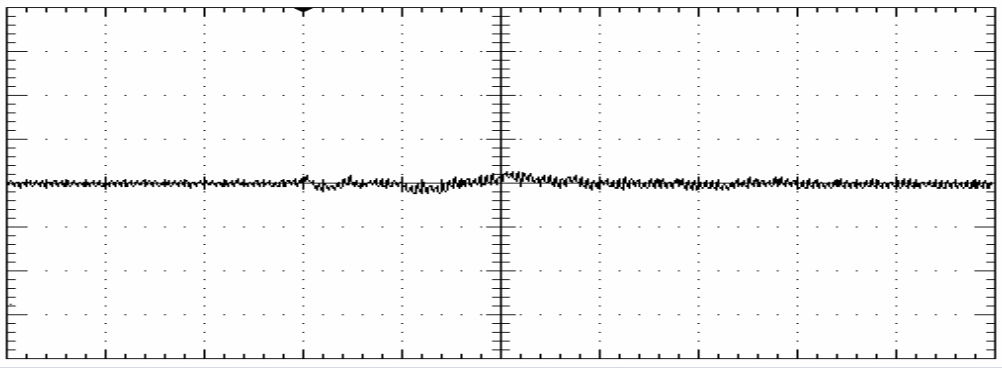
(b) Proposed optimal control algorithm

(X axis: 40us/div; Y axis: 50mv/div)

Output Voltage Response to Input Step from 5V to 7.5V



(a) Current mode PID controller



(b) Proposed optimal control algorithm

(X axis: 40us/div; Y axis: 50mv/div)

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6. Conclusions

- **New optimal control algorithm to improve DC-DC converter dynamic performance proposed**
- **Capacitor charge balance is used to determine the optimal number of switching cycles to return the output to its nominal value**
- ***Minimum overshoot/undershoot and recovery time is achieved***
- **Algorithm is implemented digitally**
- **Thank you for attending … questions???**