# *Lecture-36*

# *EE5325 Power Management Integrated Circuits*

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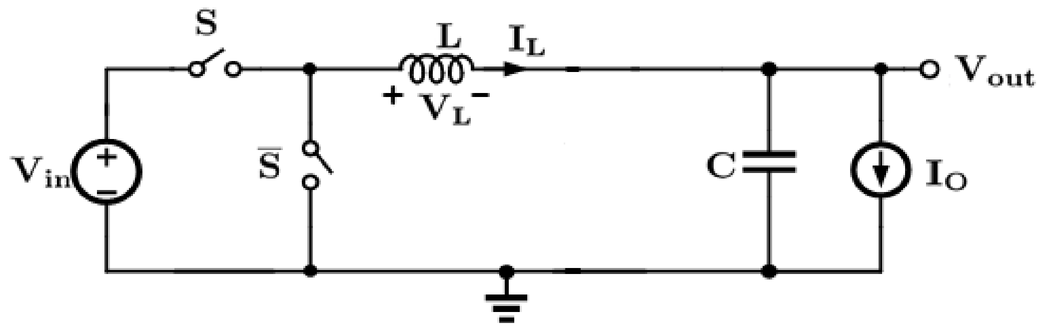
# ***Buck-Boost Converter***

# Types of DC-DC converter

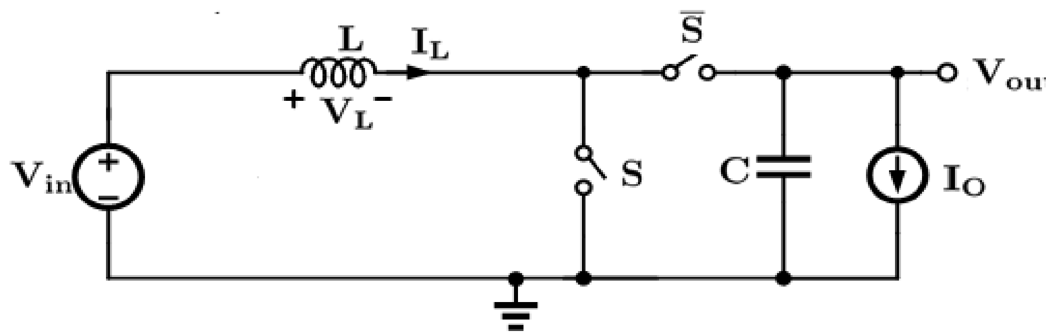
$$\mathbf{BUCK}: \frac{V_{out}}{V_{in}} < 1$$

$$V_{out} = DV_{in},\ I_L = I_o$$




$$\mathbf{BOOST}: \frac{V_{out}}{V_{in}} > 1$$

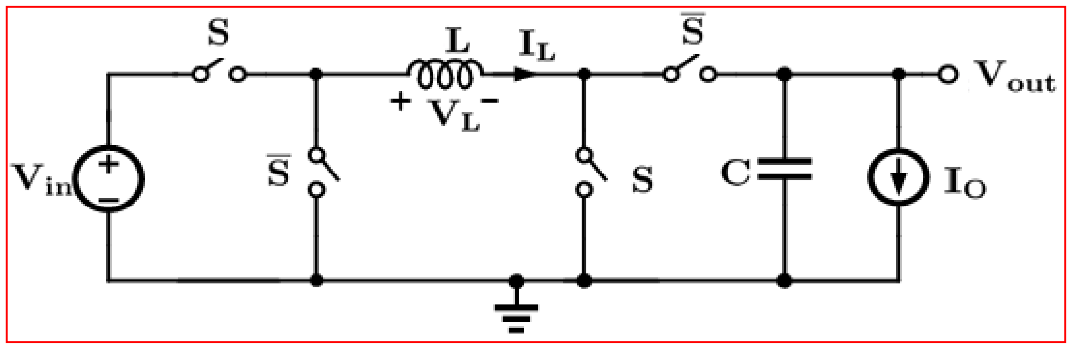
$$V_{out} = \frac{1}{1-D} V_{in},\ I_L = \frac{1}{1-D} I_o$$




$$\mathbf{BUCK\text{-}BOOST}: \frac{V_{out}}{V_{in}} \approx 1$$

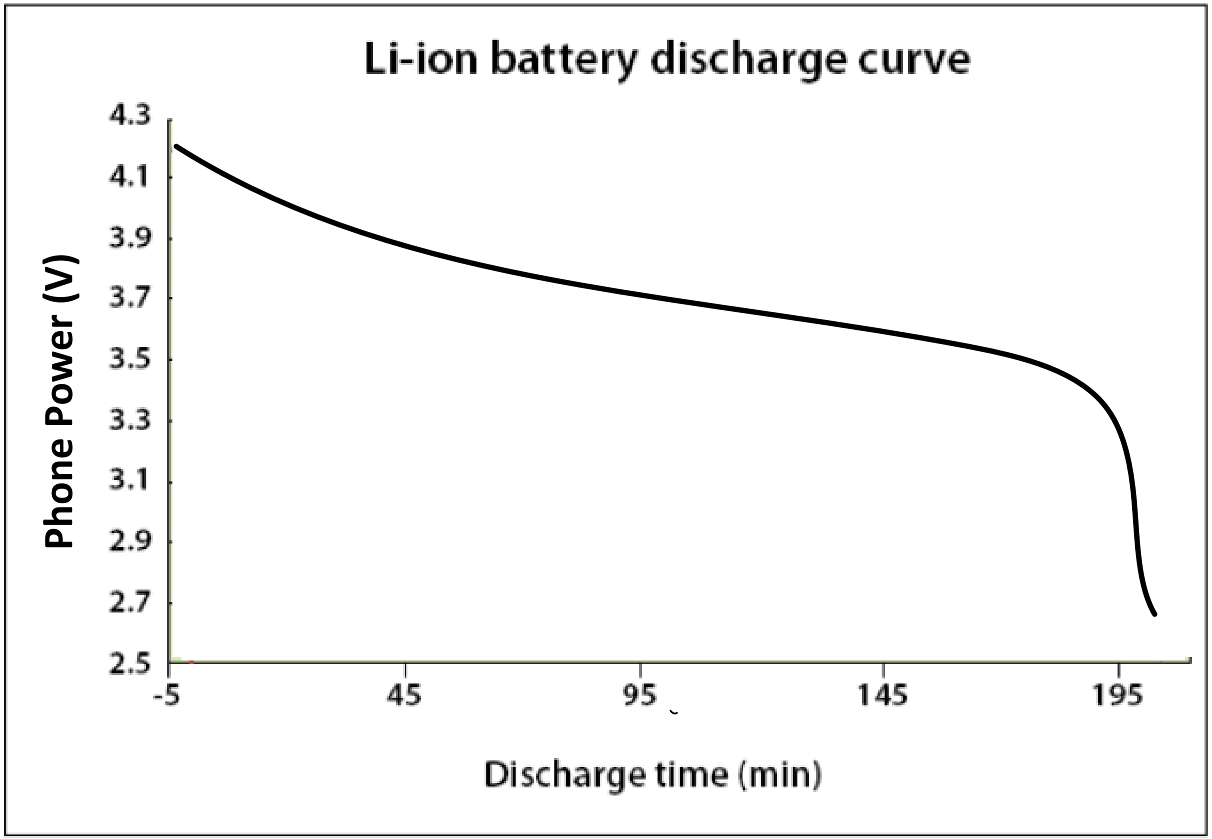
$$V_{out} = \frac{D}{1-D} V_{in},\ I_L = \frac{1}{1-D} I_o$$

Also works as buck only or boost only

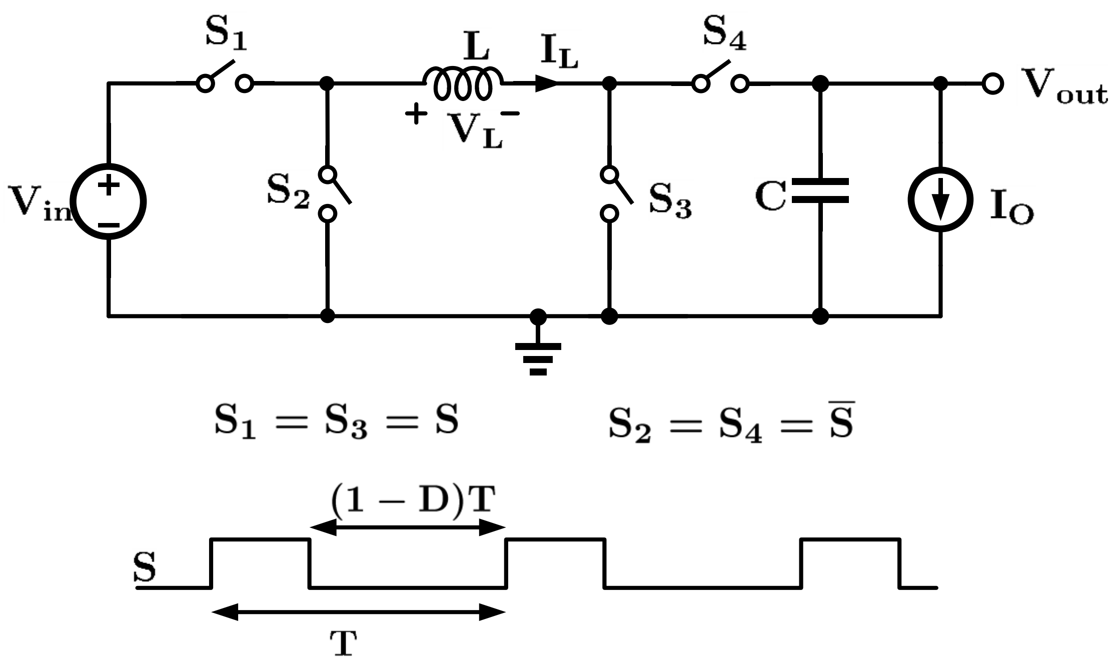


# Why Buck-Boost?

- Considering the Li-ion battery discharge profile, either buck or boost fails to operate for the output voltage of 3.3V - 3.6V
  - Converter needs to be operated in buck-boost mode for most of the time



# Drawback of Conventional BB converter

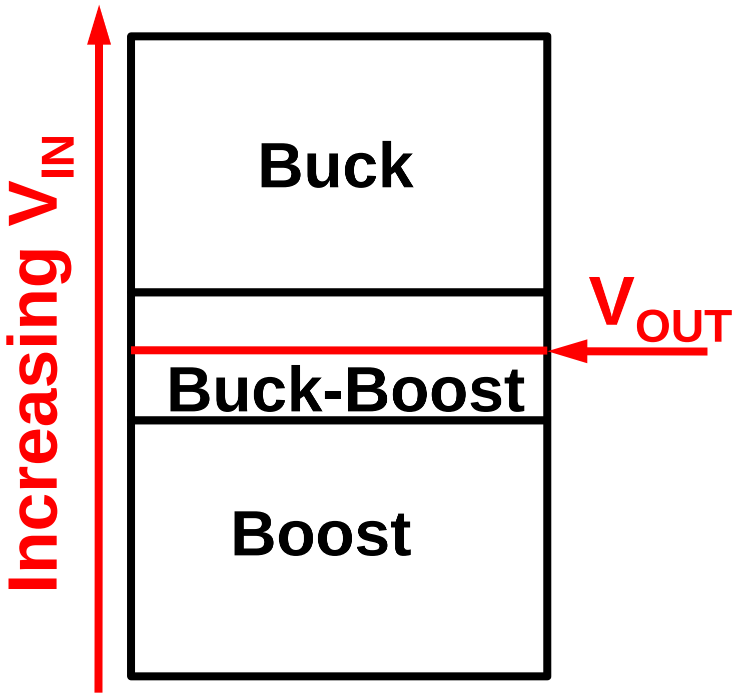



$$V_{out} = \frac{D}{1-D} V_{in} \qquad (1)$$

$$I_L = \frac{1}{1-D} I_o \qquad (2)$$

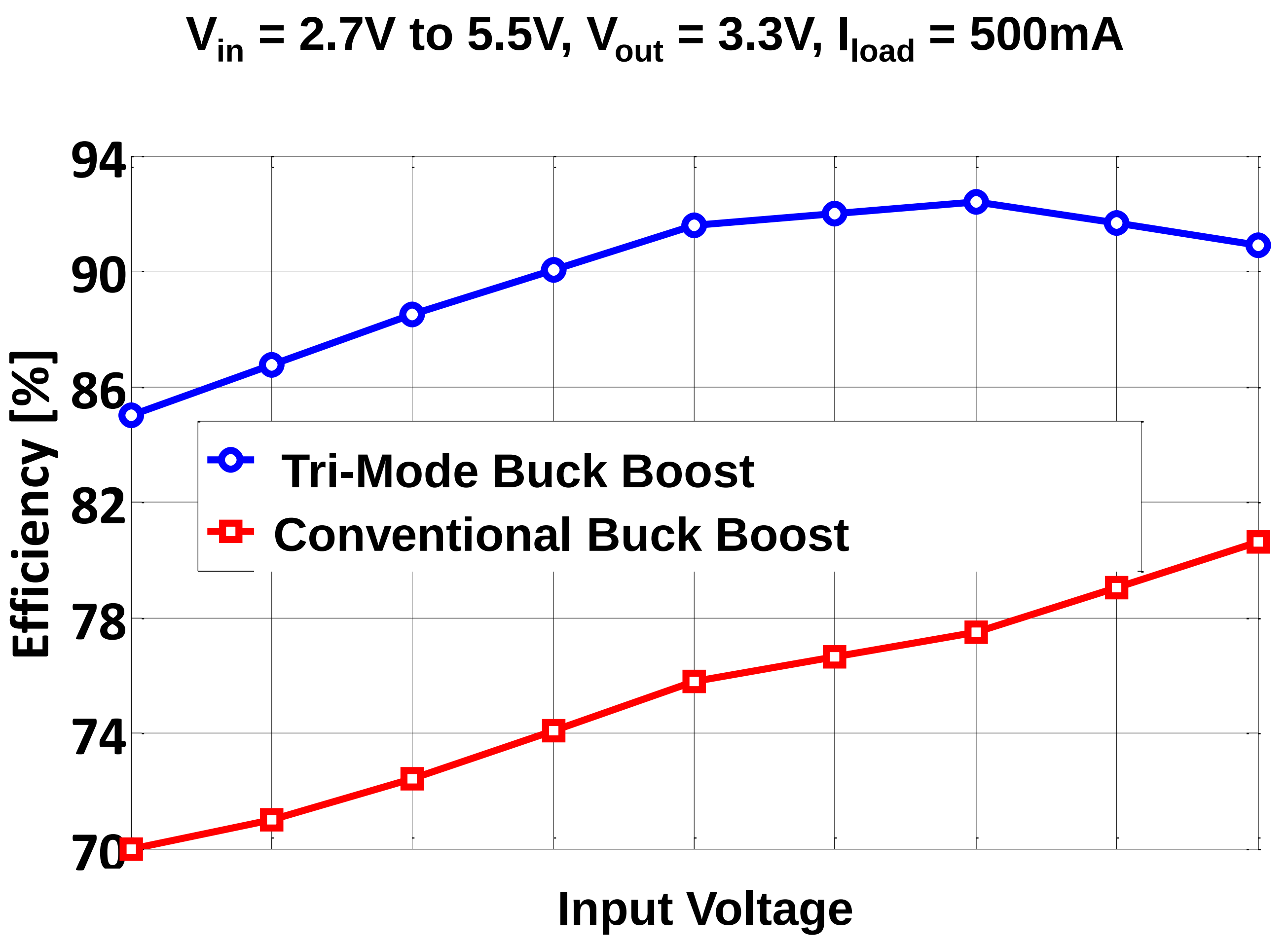
- Single Duty cycle, D, controls all the switches.
- Switching losses are higher due to simultaneous operation of 4 switches
- Conduction losses are higher due to larger Inductor current (nearly 2x when Vin ≈ Vout.

# Tri-Mode Operation of BB Converter

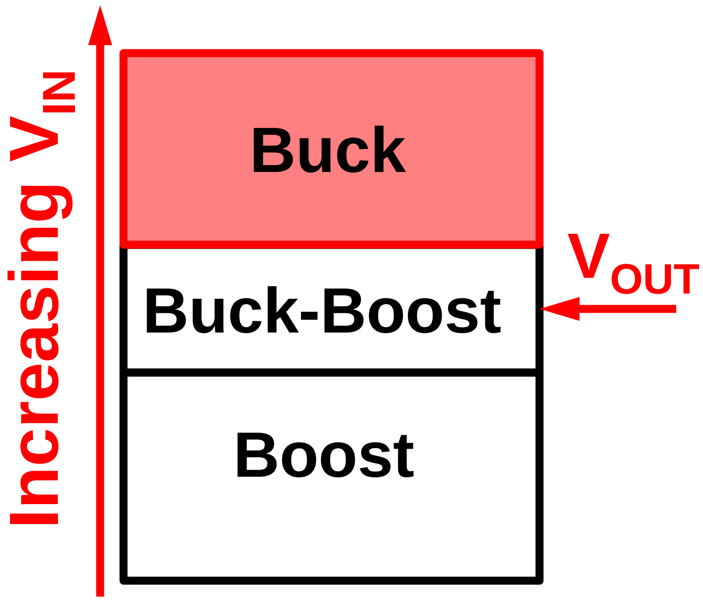


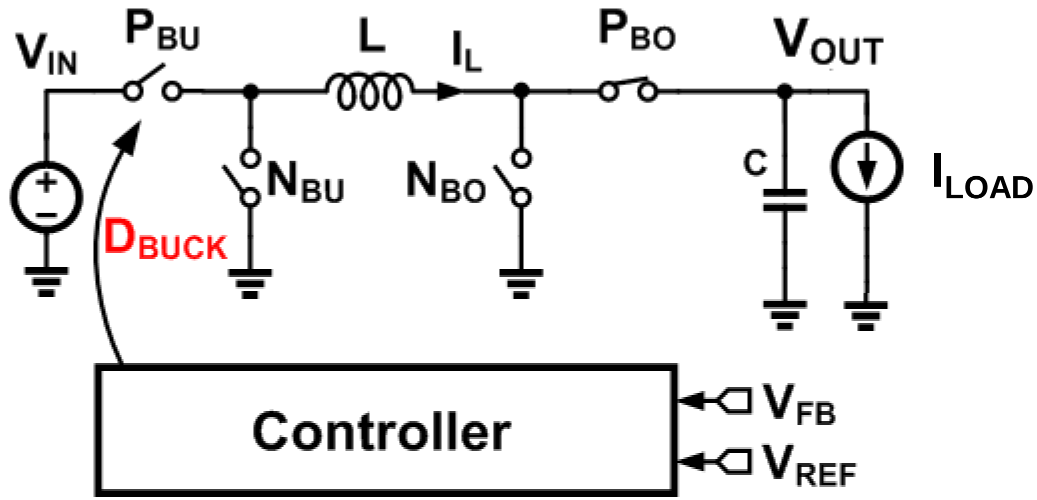

- $V_{IN} > V_{OUT}$ : Buck Mode
- $V_{IN} < V_{OUT}$ : Boost Mode
- $V_{IN} \sim V_{OUT}$ : Buck-Boost Mode

# Conventional vs. Tri-Mode Efficiency



# Tri-Mode: Buck



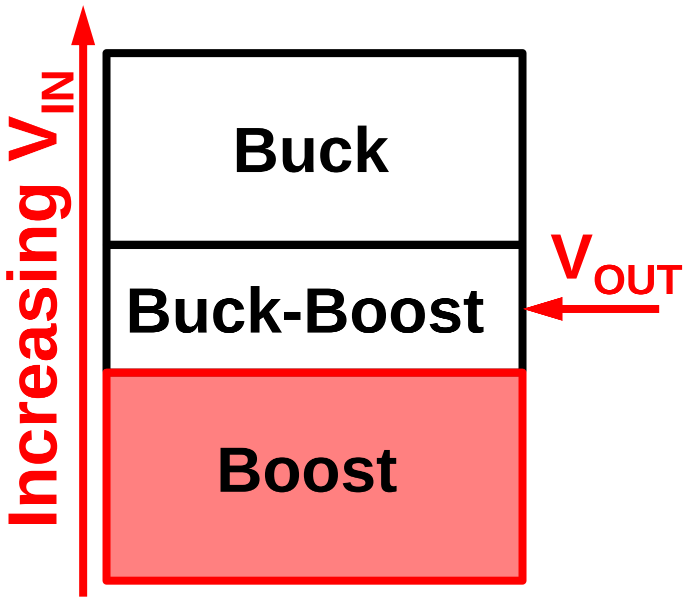



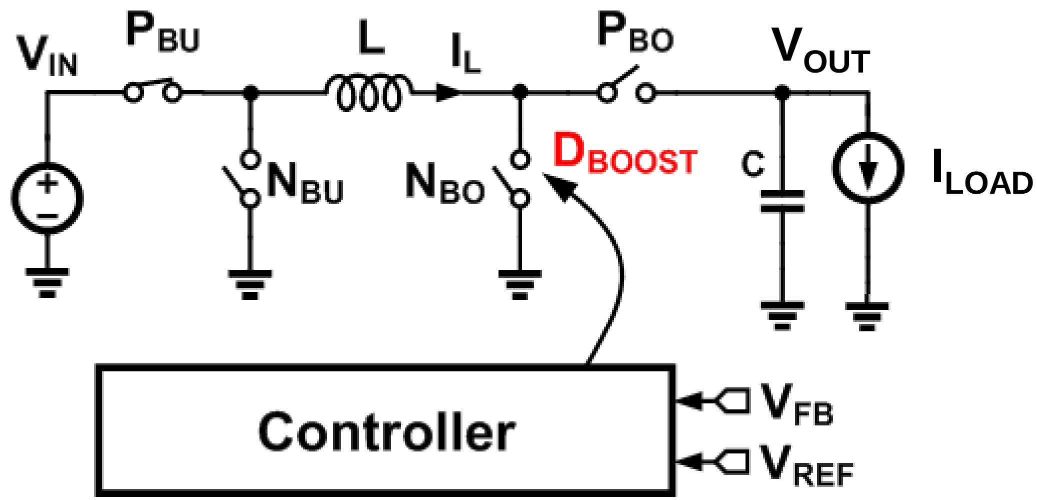

- $P_{BO}$ always ON
- $D_{BUCK}$ controls buck switches

$$V_{OUT} \approx (D_{BUCK})V_{IN}$$

$$I_L = I_{LOAD}$$

# Tri-Mode: Boost



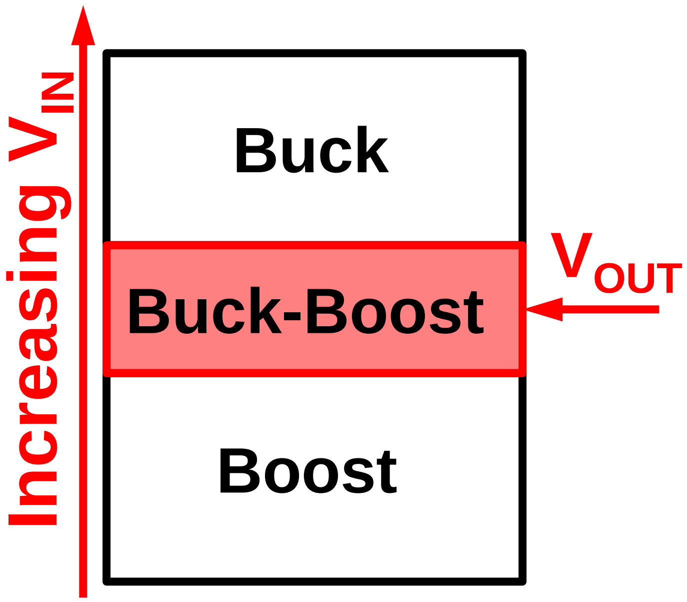



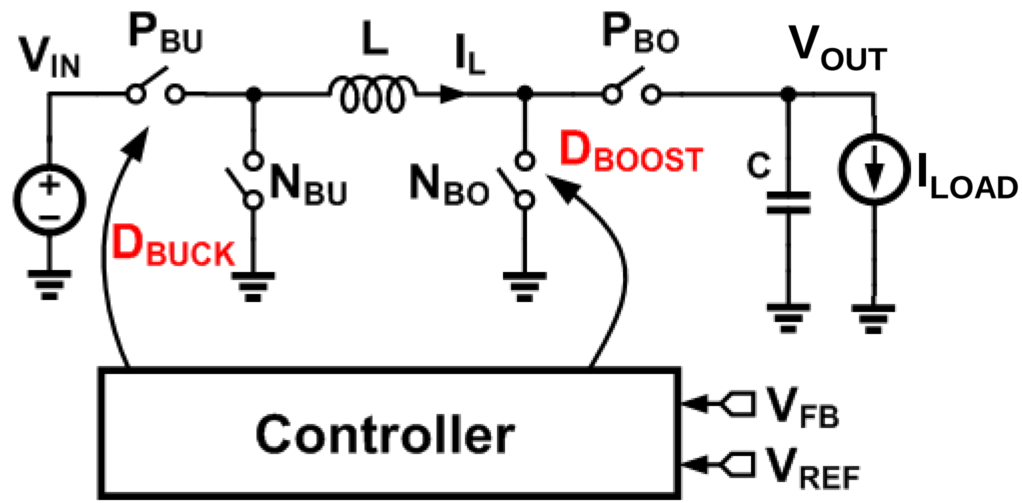

- $P_{BU}$ always ON
- $D_{BOOST}$ controls boost switches

$$V_{OUT} \approx \frac{V_{IN}}{(1 - D_{BOOST})}$$

$$I_L = \frac{I_{LOAD}}{(1 - D_{BOOST})}$$

# Tri-Mode: Buck-Boost



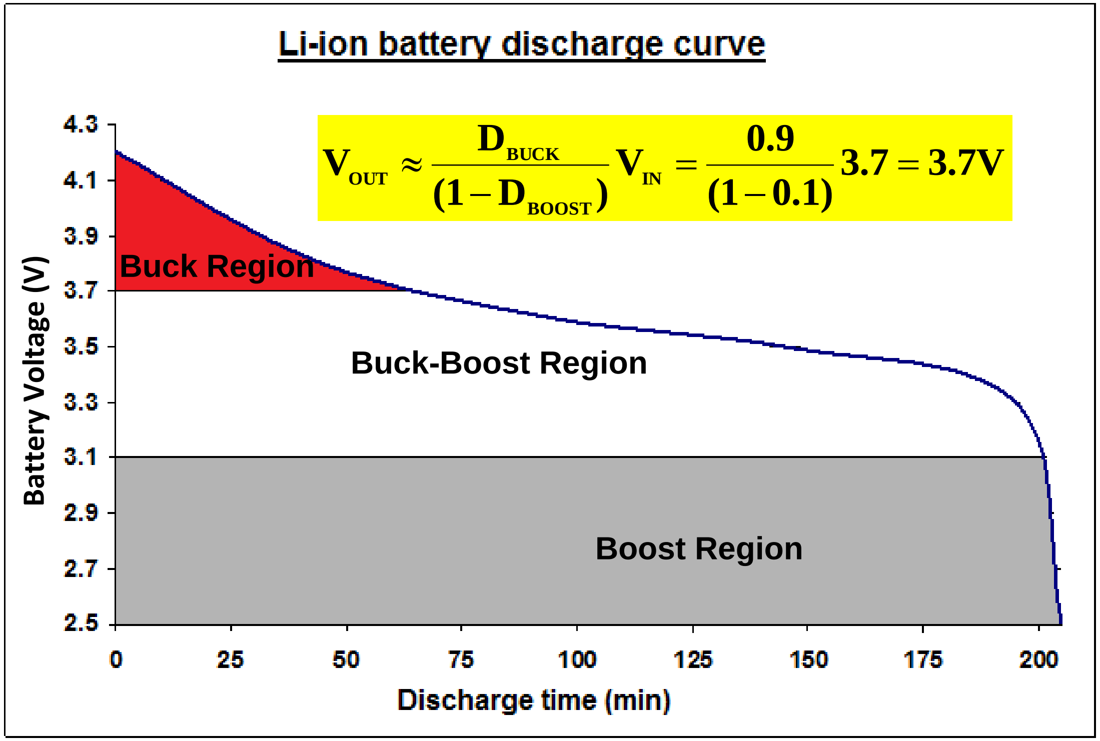




- $D_{BUCK}$ controls buck switches
- $D_{BOOST}$ controls boost switches

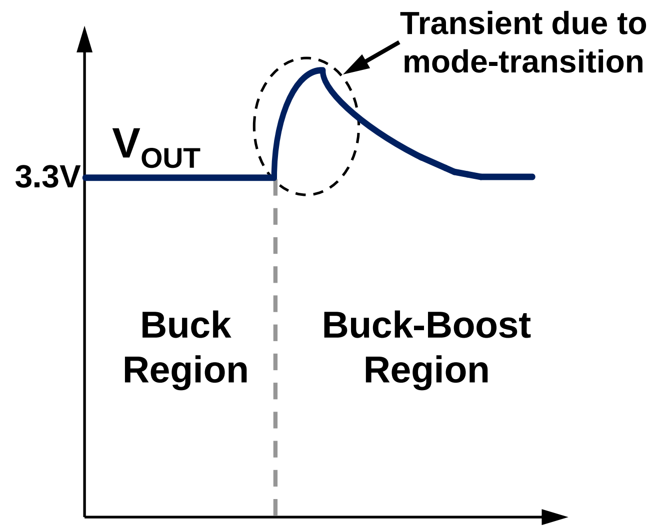
$$V_{OUT} \approx \frac{D_{BUCK}}{(1-D_{BOOST})} V_{IN}$$

$$I_L = \frac{I_{LOAD}}{1-D_{BOOST}}$$

# Issue with Tri-Mode Buck-Boost




$$\text{Buck Mode}: D_{BOOST} = 0$$
$$\text{Boost Mode}: D_{BUCK} = 1$$

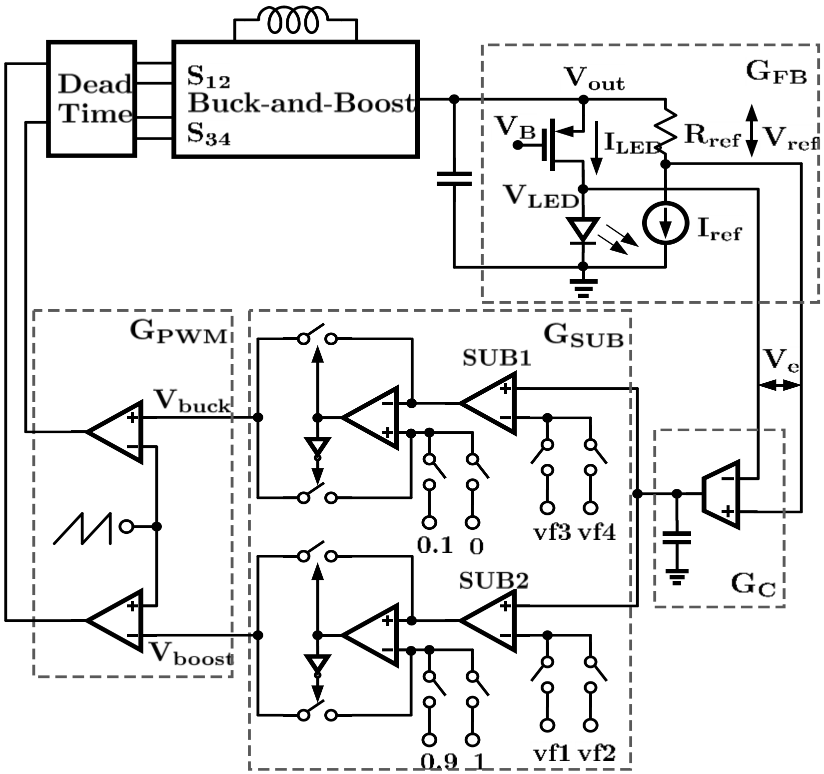



- **Mode transition causes large voltage transient**
- **Boundary condition must be satisfied**
  - **Varies with load current and losses**

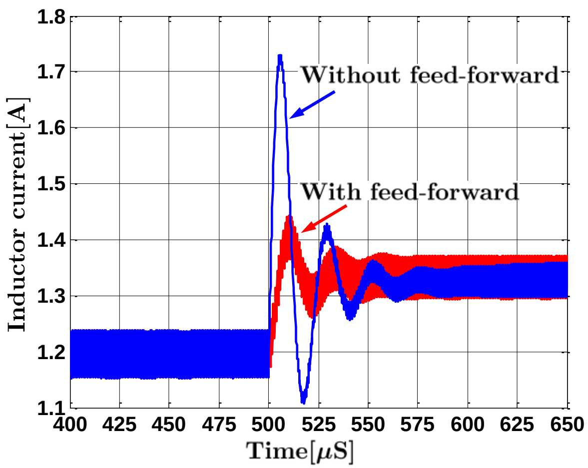
**Boundary Condition**

$$V_{OUT}(\text{buck}) = V_{OUT}(\text{buck-boost})$$
$$\rightarrow D_{BUCK\_max} = \frac{D_{BUCK}}{1-D_{BOOST\_min}}$$
$$\rightarrow D_{BUCK} = D_{BUCK\_max} \cdot (1-D_{BOOST\_min})$$

# Solutions for Mode Transitions



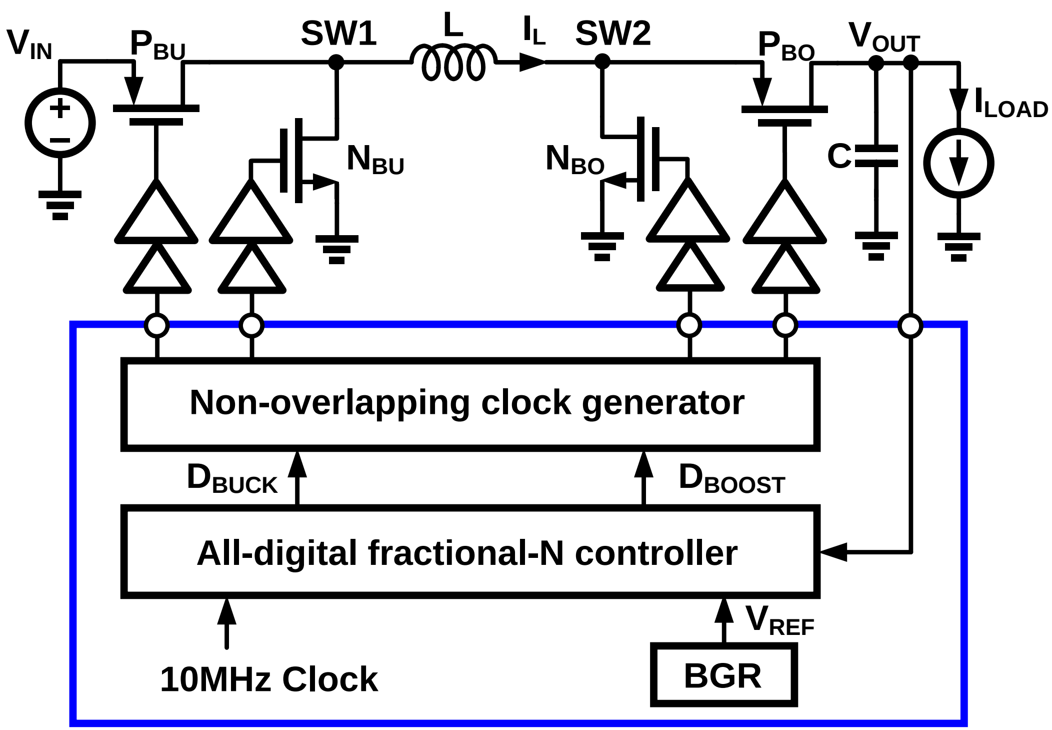

- **Appropriate Feed-forward voltage vf1 - 4 is subtracted to instantaneously change the duty cycles during mode transition.**
- **Analog Implementation makes is susceptible to PVT and requires external compensation capacitor**




S. Bang, D. Swank, A. Rao, W. McIntyre, Q. Khan and P. K. Hanumolu, 1.2A 2MHz tri-mode Buck-Boost LED driver with feed-forward duty cycle correction, *CICC*, Sept. 2010.

# Digital Constant ON/OFF Time Buck-Boost Converter

- **Uses constant ON/OFF technique**
- **Enables High Switching Frequency Operation**
- **All digital implementation eliminates the need of external compensation capacitor**



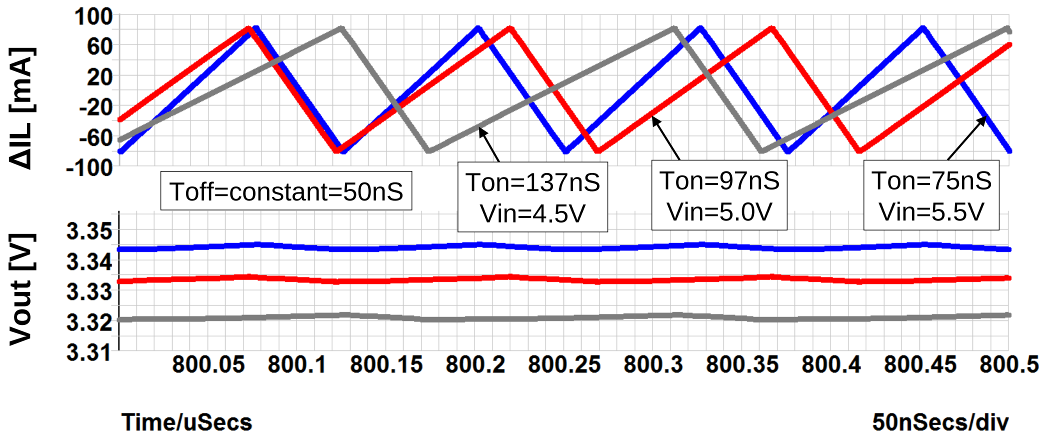

Q. Khan, et al, "A 3.3V 500mA Digital Buck-Boost Converter with 92% Peak Efficiency Using Constant ON/OFF Time Delta-Sigma Fractional-N Control, *Proc. ESSCIRC '11*, Sept. 2011.

# Constant ON/OFF Time Operation

$$\text{Inductor ripple current, } \Delta I_L = \frac{V_{IN} - V_{OUT}}{L} T_{ON} \qquad (1)$$

$$T_{ON} = D \cdot T \qquad T_{OFF} = (1 - D) \cdot T$$

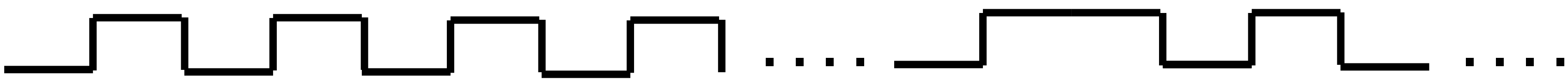
- **Max ripple occurs at D=0.5 (Ton = Toff)**
  - **The converter can be operated at high switching frequency when D=0.5**
- **From eq. 1, D increases with Vin**
  - **Fixing OFF time and making ON time function of Vin does not affect the inductor ripple**
  - **Causes variable switching frequency**



# Fractional-N Control

**Buck Mode:**

N cycles of 50% Buck : 1 cycle of 100% Buck



**50% Buck**

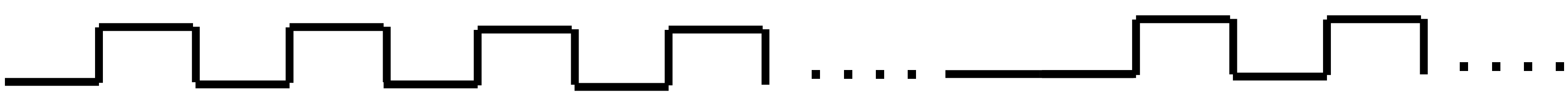
**100% Buck**

**Buck-Boost Mode:**

1 cycle of 50% Buck : 1 cycle of 50% Boost

**Boost Mode:**

N cycle of 50% Boost : 1 cycle of 0% Boost

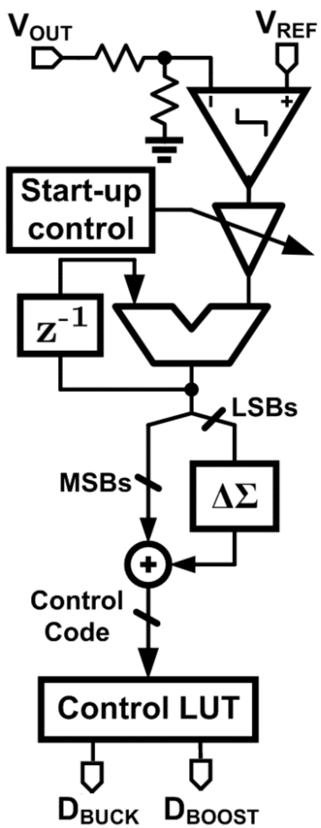


**50% Boost**

**0% Boost**

# Fractional-N Control Logic

- Predefined states are stored in the lookup table providing the coarse voltages
- Uses 18-bit acc for integrating the error (4 MSBs, 7 LSBs, 7 dropped bits.
- Any intermediate states are resolved by ΔΣ Modulator




| Operating States | Control Code | Fraction N:1 |
|---|---|---|
| | | 50%Buck:100%Buck |
| ST1 | 0001 | 5:1 |
| ST2 | 0010 | 4:1 |
| ST3 | 0011 | 3:1 |
| ST4 | 0100 | 2:1 |
| ST5 | 0101 | 1:1 |
| | | 50%Buck:50%Boost |
| ST6 | 0110 | 1:1 |
| | | 50%Boost:0%Boost |
| ST7 | 0111 | 1:1 |
| ST8 | 1000 | 2:1 |
| ST9 | 1001 | 3:1 |
| ST10 | 1010 | 4:1 |
| ST11 | 1011 | 5:1 |

Buck Mode (ST1–ST5)

Buck-Boost Mode (ST5–ST7)

Boost Mode (ST7–ST11)

5.5V → Decreasing $V_{IN}$ → 2.7V

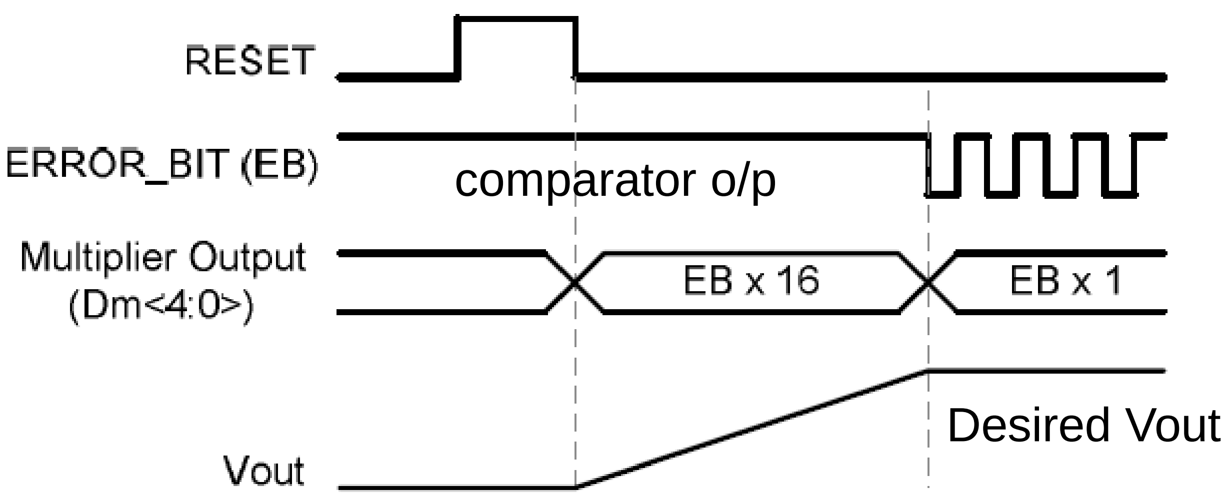
# Start-up Control

- **Startup time is the function of no. of bits dropped in the accumulator and converter resolution**

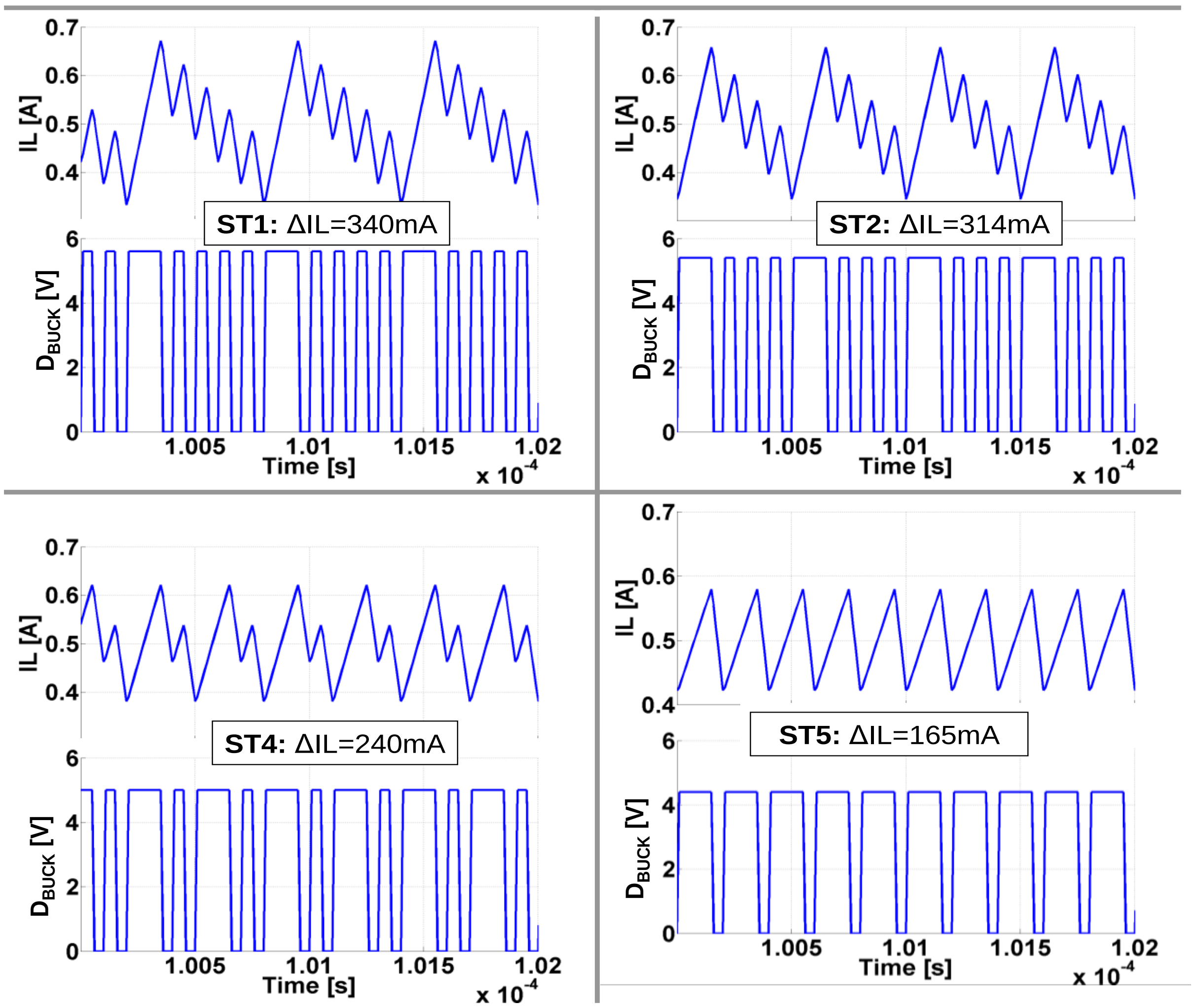
- **No. of ACC bits dropped = 7**

  **→ The startup time may be more than 10ms**

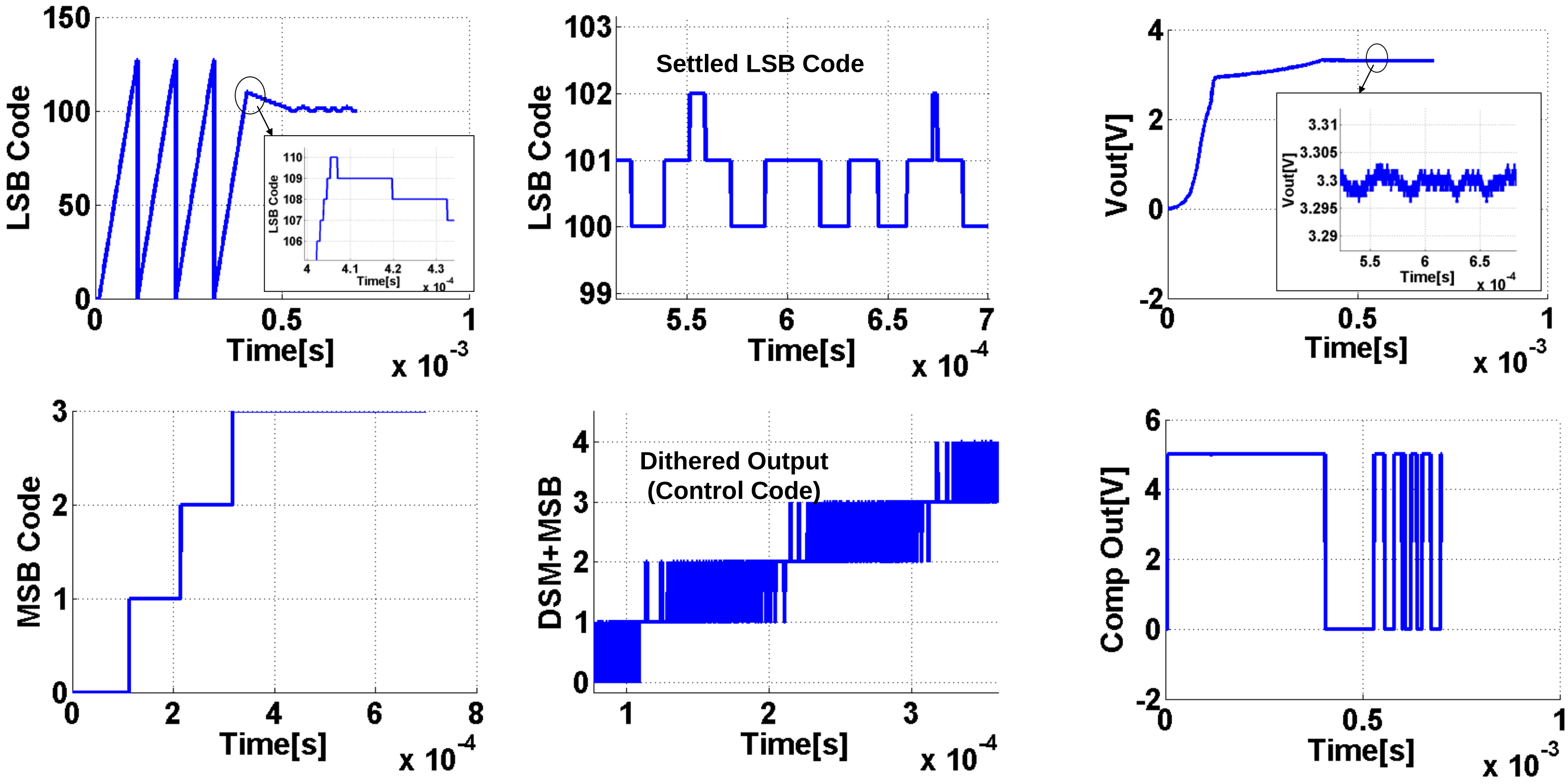
- **Speeded up by dropping only 3 bits in accumulator and switch to 7 bits once the output settles**



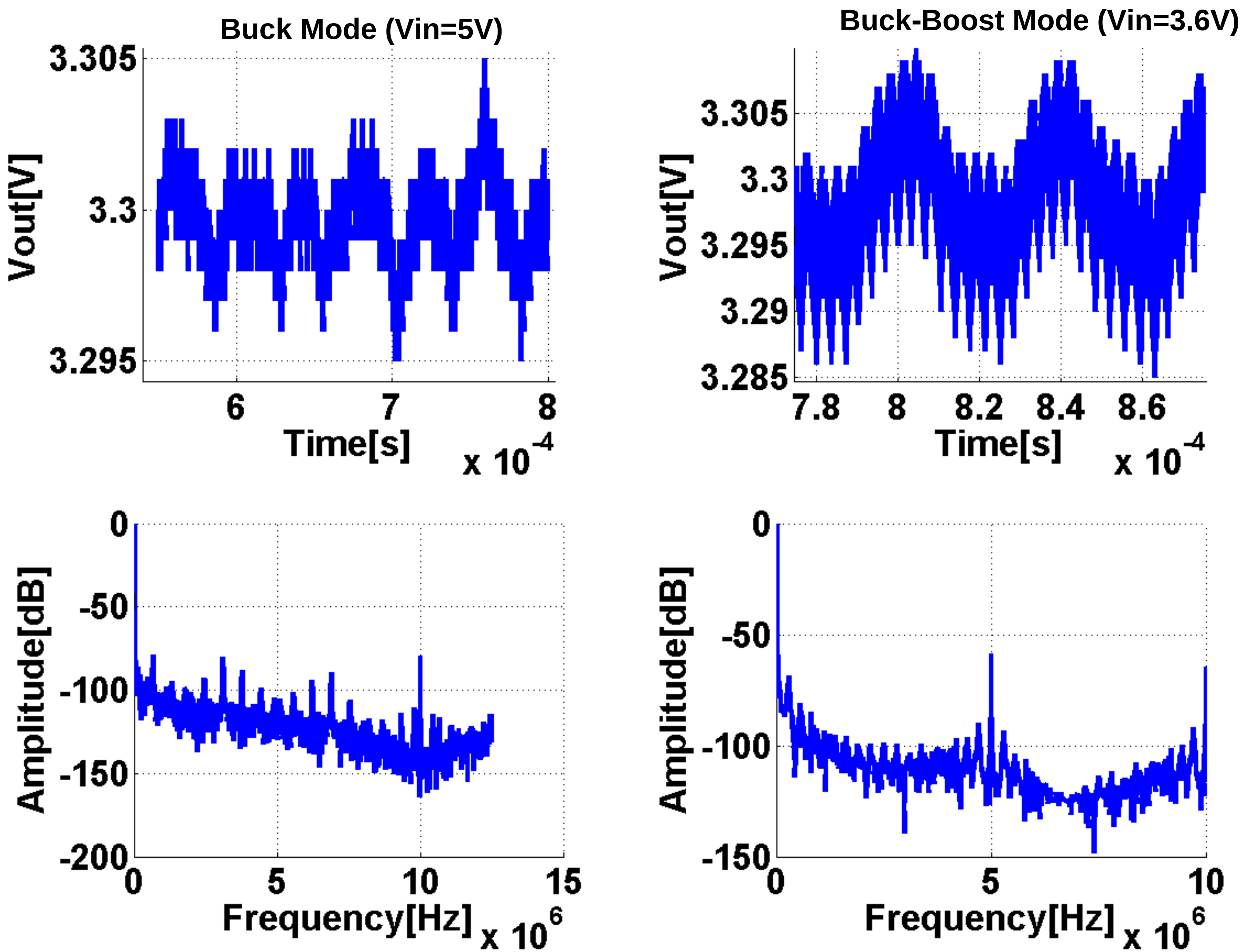
# Inductor Current Profile



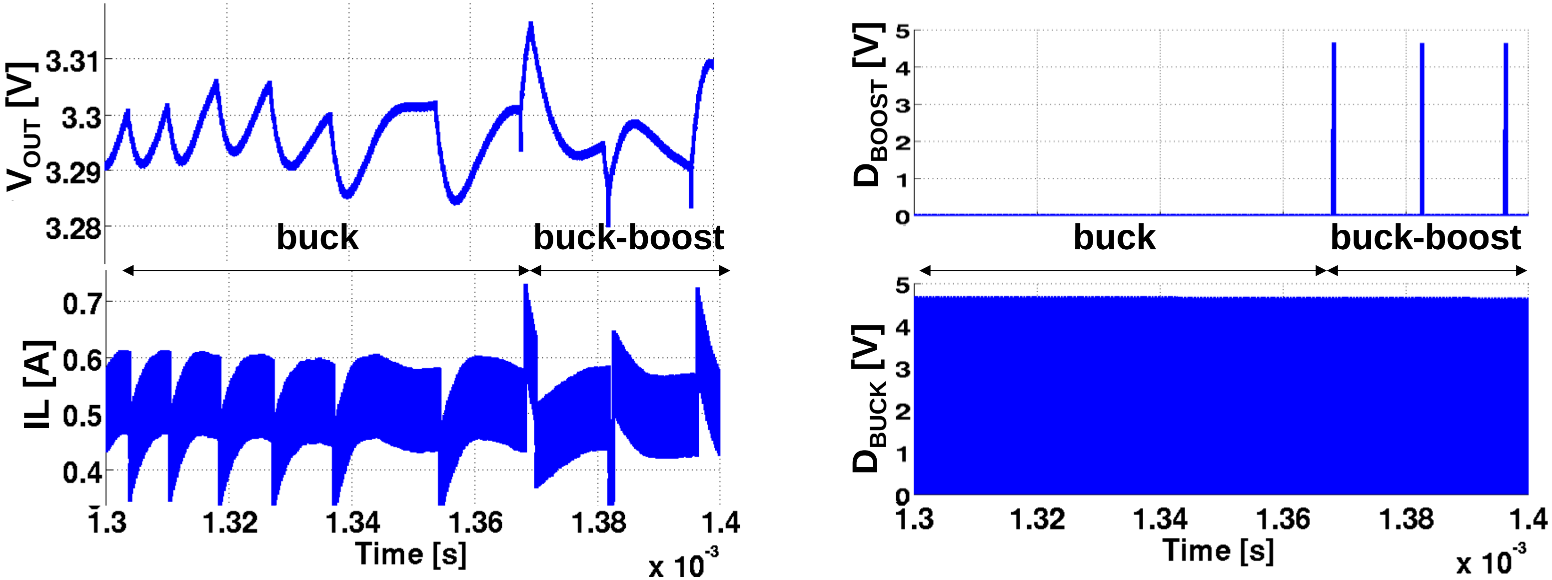
# Controller Response



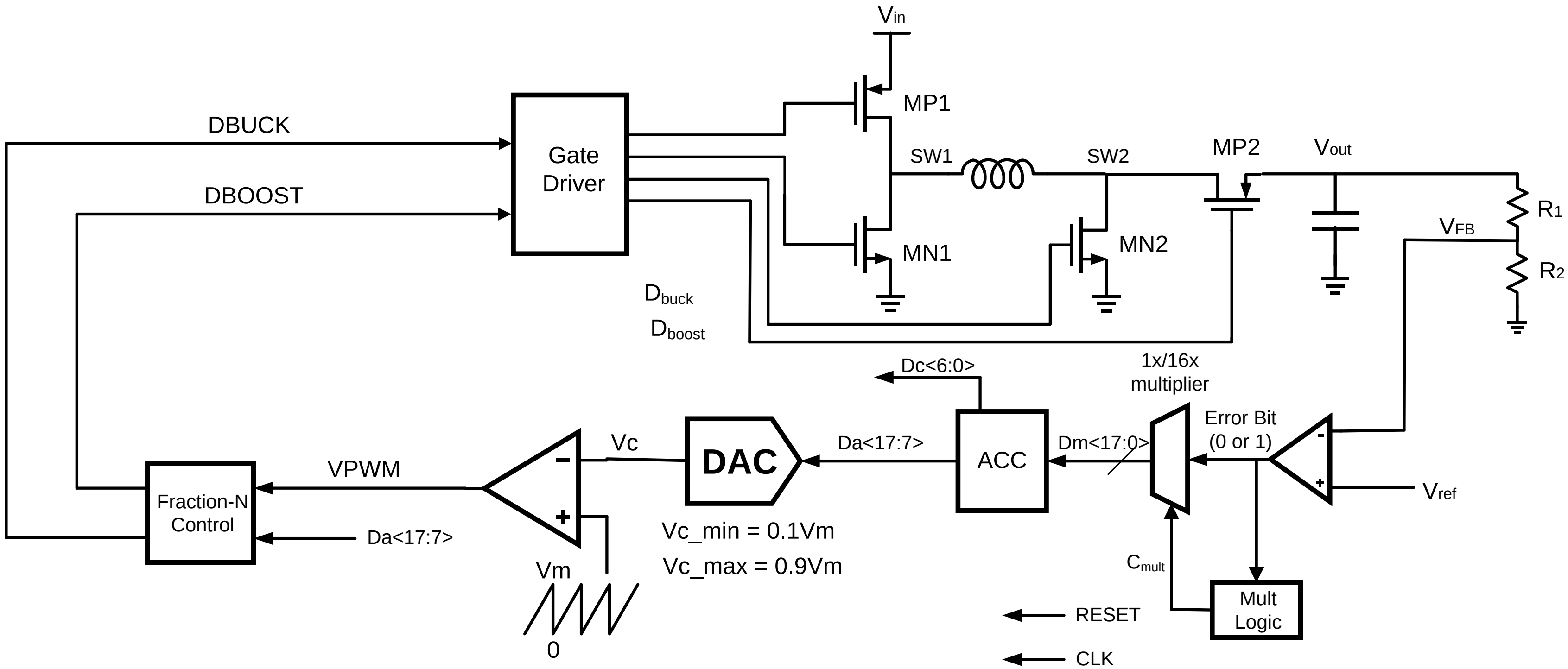
# Output Voltage Ripple



# Mode Transition



# Hybrid PWM Fractional-N Control




| Buck Mode | Buck-Boost Mode (Fractional-N) | Boost Mode |
|---|---|---|
| DBOOST = 0<br>DBUCK = VPWM | 90%Buck:100%Buck<br>90%Buck:10%Boost<br>10%Boost:0%Boost | DBOOST = VPWM<br>DBUCK = 1 |