1. Basic Configuration of a Buck-Boost Converter

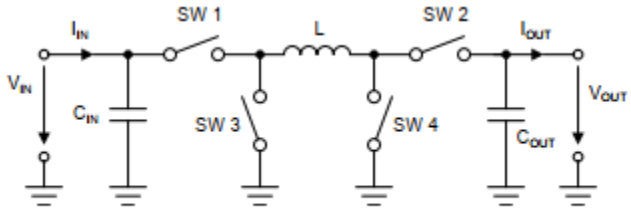
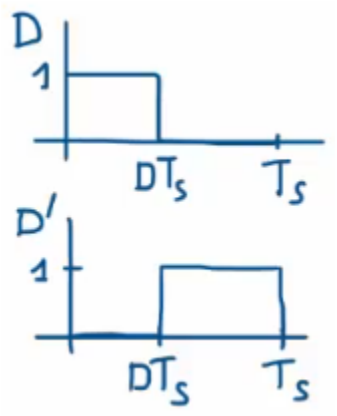


Figure 1. Buck-Boost Converter Schematic

2. Operating Principle

$\overline{D} = 1 - D$



2.1 Synchronize Buck

$$D = \frac{V_o}{V_i}$$

$V_i > V_o$

Only two switches commutate.

Can't operate with $V_i = V_o$ or $D = 1$.

Q3 is fully turned on and Q4 is fully turned off. Q1 and Q2 are controlled by D and 1-D, respectively, the converter becomes a synchronize buck converter, as shown in Figure 4.

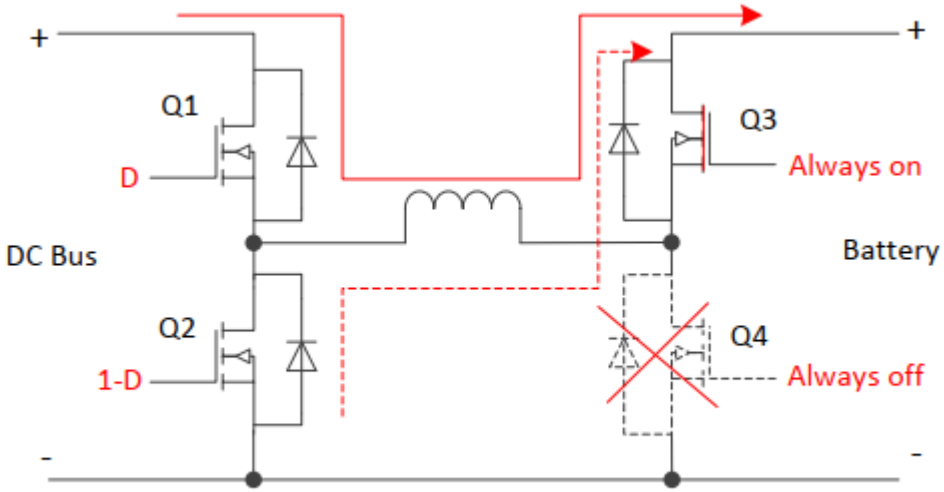


Figure 4. Synchronize Buck in Charge Mode

2.2 Synchronize Boost

$$D = 1 - \frac{V_i}{V_o}$$

Only two switches commutate.

Can't operate with $V_i = V_o$ or $D = 0$.

Q1 is fully turned on and Q2 is fully turned off. Q4 and Q3 are controlled by D and 1-D, respectively, the converter becomes a synchronize boost converter, as shown in Figure 5.

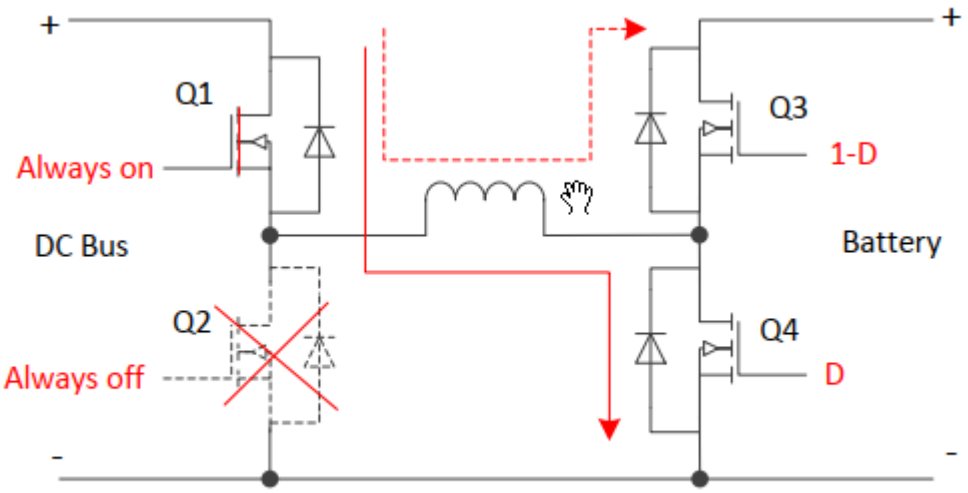


Figure 5. Synchronize Boost in Charge Mode

2.3 Synchronize Buck-Boost

$$D = \frac{V_o}{V_i + V_o}$$

$V_i \approx V_o$

Four switches commutate.

Can operate with $V_i = V_o$ or $D = 0.5$.

Higher switches losses.

Lower efficiency.

Q1 and Q4 are controlled by D, Q2 and Q3 are controlled by 1-D. The converter becomes a synchronize buck-boost converter, as shown in Figure 6.

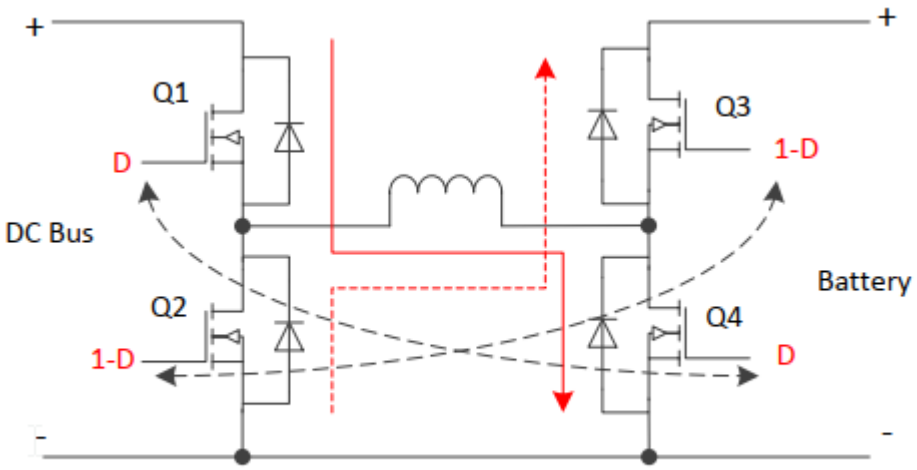


Figure 6. Synchronize Buck-Boost in Charge Mode

3. Operation mode

The 4-switch power stage changes its operation mode according to DC Bus and battery voltage, as shown in Figure 10. To prevent mode from bouncing, hysteresis is added between the buck and buck-boost modes and between the buck-boost and boost modes.

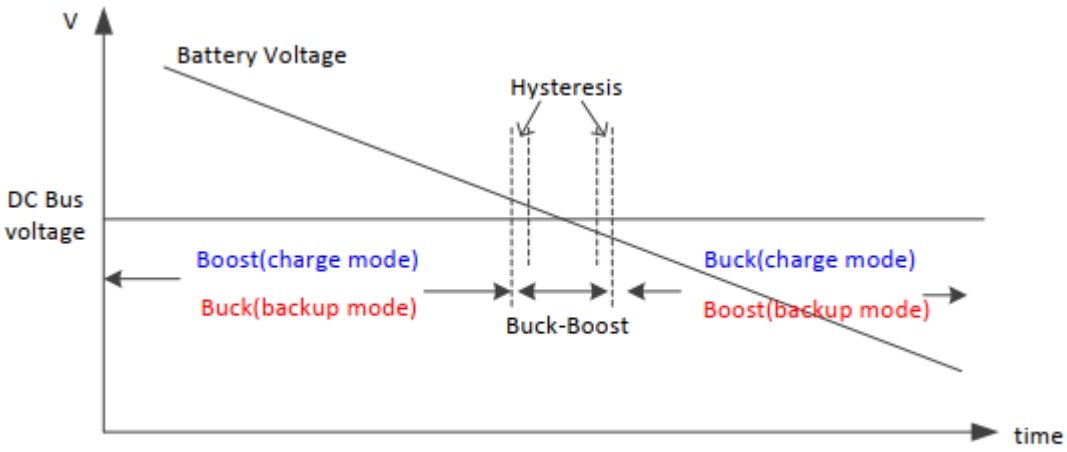
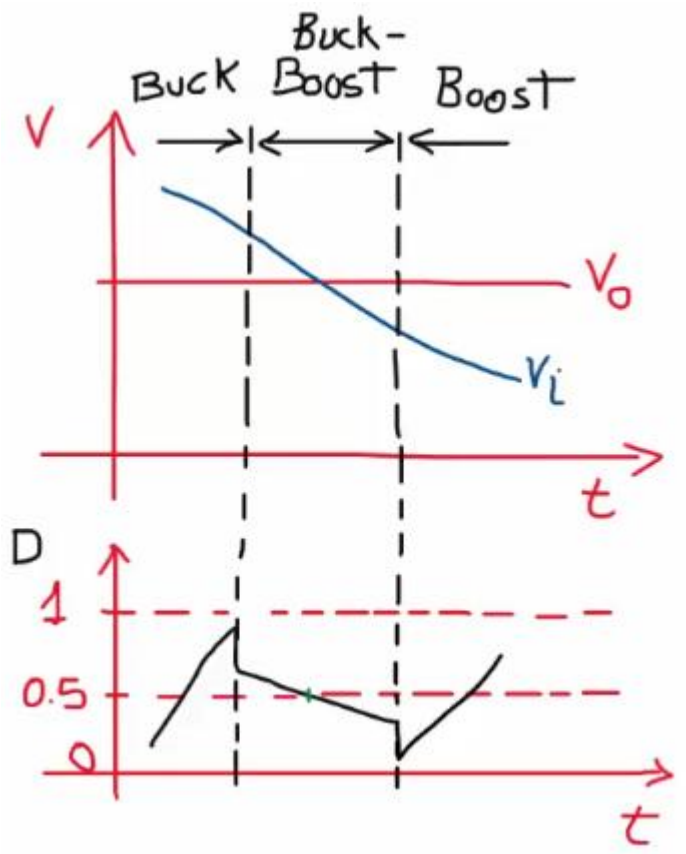
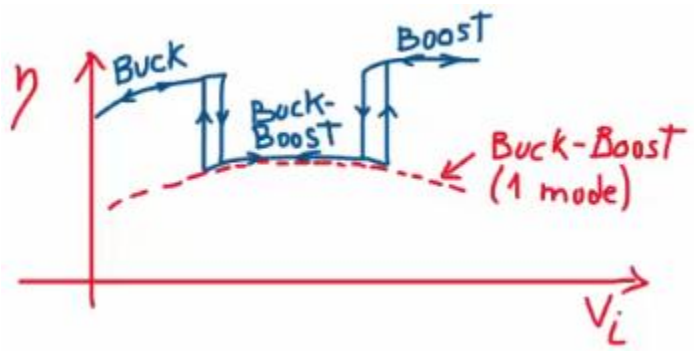


Figure 10. Operation modes vs. DC Bus and battery voltage





Closed-loop compensator must be designed for stable operation.

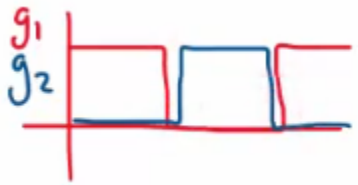
Transient perturbations during mode changes.

4. Implementation

MOSFETs used as switches.

High-side switches (S1, S3) need to be driven.

Dead time must be added to avoid shoot-through current.



Bootstrap cannot be used: it can't keep high-side switches continuously on.

Typical solutions: transformer-based gate drivers, optocoupler-based gate drivers.

4.1 Buck

$$D = \frac{V_o}{V_i}$$

$$L = \frac{1}{f\Delta i_L} * \left(V_o - \frac{V_o^2}{V_i}\right)$$

$$C = \frac{\Delta i_L}{8f\Delta V_o}$$

4.2 Buck-Boost

$$D = \frac{V_o}{V_o + V_i}$$

$$L = \frac{1}{f\Delta i_L} * \frac{V_o}{1 + \frac{V_o}{V_i}}$$

$$C = \frac{I_o}{f\Delta V_o} * \frac{V_o}{V_o + V_i}$$

4.3 Boost

$$D = \frac{V_o - V_i}{V_o}$$

$$L = \frac{1}{f\Delta i_L} * \left(V_i - \frac{V_i^2}{V_o}\right)$$

$$C = \frac{I_o}{f\Delta V_o} * \frac{V_o - V_i}{V_o}$$

5. Design example

Input voltage range: $V_i = [35,70]$ V

Duty cycle range: $D = [0.1,0.85]$

Output voltage: $V_o = 48$ V

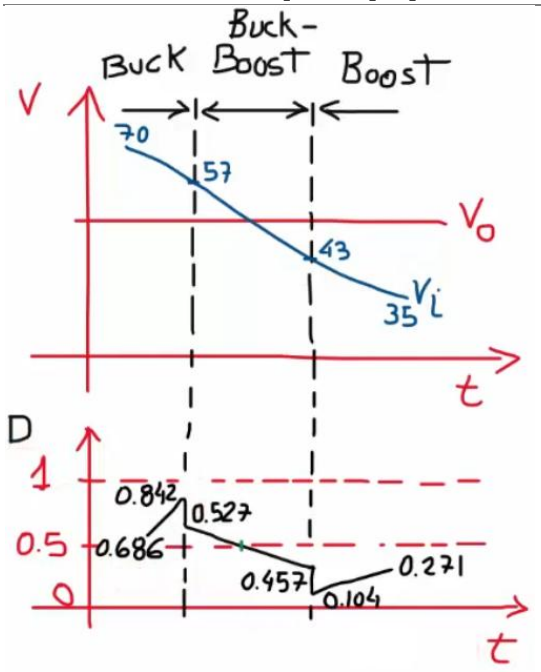
Output current: $I_o = 2$ A

Switching frequency: $f = 100$ kHz

Inductor current ripple: 0.6 A (30%)

Output voltage ripple: 1 V (2%)

Operating mode	Vi	D	Vi/Vo
Buck	[57-70]	[0.686,0.842]	1.1875
Buck-boost	[43,57]	[0.457,0.527]	-
Boost	[35,43]	[0.104,0.271]	0.8958



5.1 Inductor and Capacitor (Buck)

$$L_{max} = \frac{1}{f\Delta i_L} * \left(V_o - \frac{V_o^2}{V_{i_{max}}}\right) = \frac{1}{100 * 10^3 * 0.6} * \left(48 - \frac{48^2}{70}\right) = 0.251 \text{ mH}$$

$$C = \frac{\Delta i_L}{8f\Delta V_o} = \frac{0.6}{8 * 100 * 10^3 * 1} = 0.75 \text{ uF}$$

5.2 Inductor and Capacitor (Buck-Boost)

$$L_{max} = \frac{1}{f\Delta i_L} * \frac{V_o}{1 + \frac{V_o}{V_{i_{max}}}} = \frac{1}{100 * 10^3 * 0.6} * \frac{48}{1 + \frac{48}{57}} = 0.434 \text{ mH}$$

$$C_{max} = \frac{I_o}{f\Delta V_o} * \frac{V_o}{V_o + V_{i_{min}}} = \frac{2}{100 * 10^3 * 1} * \frac{48}{48 + 43} = 10.6 \text{ uF}$$

5.3 Inductor and Capacitor (Boost)

$$V_i > \frac{V_o}{2}$$

$$L_{max} = \frac{1}{f\Delta i_L} * \left(V_{i_{min}} - \frac{V_{i_{min}}^2}{V_o}\right) = \frac{1}{100 * 10^3 * 0.6} * \left(35 - \frac{35^2}{48}\right) = 0.158 \text{ mH}$$

$$C_{max} = \frac{I_o}{f\Delta V_o} * \frac{V_o - V_{i_{min}}}{V_o} = \frac{2}{100 * 10^3 * 1} * \frac{48 - 35}{48} = 5.42 \text{ uF}$$

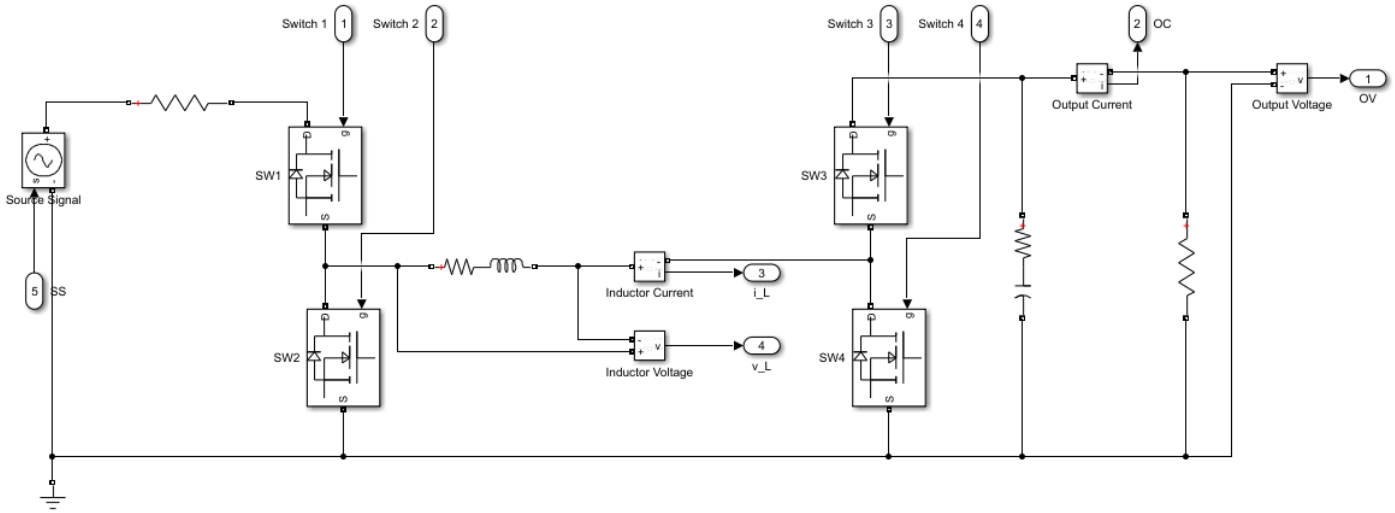
5.4 Verification

$L = 0.434$ mH

$C = 10.6$ uF

Operating mode	Vi (V)	D	Vi/Vo	Δi_L (A)	ΔV_o (V)
Buck	[57,70]	[0.686,0.842]	1.1875	[0.175,0.348]	0.071
Buck-boost	[43,57]	[0.457,0.527]	-	[0.522,0.6]	[0.806,1]
Boost	[35,43]	[0.104,0.271]	0.8958	[0.103,1.218]	[0.196,0.511]

5.5 Simulink implementation



Mode	AB	SW1	SW2	SW3	SW4
Buck	00	D	1 - D	1	0
Buck-Boost	01	D	1 - D	1 - D	D
Boost	11	1	0	1 - D	D
Off	10	0	0	0	0

$SW1 = \bar{A}D + AB$

$SW2 = \bar{A}\bar{D}$

$SW3 = \bar{A}\bar{B} + B\bar{D}$

$SW4 = BD$