Boost Converter Design and Simulation

N.Hemakanth

Introduction

Boost converters play a significant role in power electronics, enabling efficient voltage step-up for various applications. These converters are widely used in renewable energy systems, portable electronics, LED drivers, and automotive systems. This article provides an in-depth exploration of the design, theoretical foundations, and simulation of a boost converter, with practical insights to help understand its working principles and applications.

1 Operating Principles of a Boost Converter

A boost converter operates on the principle of energy storage in an inductor during one part of the switching cycle and transferring that energy to the load during the other part. This process alternates between two states, depending on whether the switch (transistor) is open or closed.

State 1: Switch Closed (On)

When the switch is closed:

- The inductor is connected directly to the input source.
- The inductor stores energy as its magnetic field builds up.
- The current through the inductor increases linearly since the voltage across the inductor (v_L) is equal to the input voltage (V_s):

$$v_L = V_s = L\frac{di_L}{dt} \tag{1}$$

From this, the change in inductor current during the switch-on period ($t_{\text{on}} = D \cdot T$) can be derived as:

$$\Delta i_L = \frac{V_s \cdot D \cdot T}{L} \tag{2}$$

Where:

- D: Duty cycle (fraction of time the switch is closed).
- T: Switching period ($T = 1/f_s$, with f_s being the switching frequency).

State 2: Switch Open (Off)

When the switch is open:

- The inductor releases its stored energy, delivering it to the load via the diode.
- The inductor voltage is equal to $V_s - V_o$ (where V_o is the output voltage).
- The inductor current decreases linearly as it transfers energy to the load.

The voltage equation for the inductor during this period is:

$$v_L = V_s - V_o = L\frac{di_L}{dt} \tag{3}$$

The change in inductor current during the switch-off period ($t_{\text{off}} = (1 - D) \cdot T$) is:

$$\Delta i_L = \frac{(V_s - V_o) \cdot (1 - D) \cdot T}{L} \tag{4}$$

2 Boost Converter Design Equations

Output Voltage

For steady-state operation, the net change in inductor current (Δi_L) over a full switching cycle must be zero. Using this condition, the output voltage can be expressed as:

$$V_o = \frac{V_s}{1 - D} \tag{5}$$

Inductor Design

The inductor is a critical component, as it ensures continuous current flow and energy storage. For a boost converter operating in Continuous Conduction Mode (CCM), the minimum inductance required is:

$$L_{\text{min}} = \frac{D \cdot (1 - D)^2 \cdot R}{2 \cdot f_s} \tag{6}$$

Where R: Load resistance.

Capacitor Design

The capacitor smoothens the output voltage by reducing voltage ripple. The minimum capacitance required is:

$$C \geq \frac{D}{R \cdot f_s \cdot (\Delta V_o / V_o)} \tag{7}$$

Where $\Delta V_o/V_o$: Fractional voltage ripple allowed.

Power Relationship

In an ideal boost converter (neglecting losses):

$$P_{\text{in}} = P_{\text{out}} \tag{8}$$

$$V_s \cdot I_s = V_o \cdot I_o \tag{9}$$

3 Simulation and Results

Specifications

- **Input Voltage** (V_s): 10V – 15V
- **Output Voltage** (V_o): 48V
- **Output Power** (P_o): 0W – 100W
- **Switching Frequency** (f_s): 10 kHz

Key Design Parameters

Inductor (L): For $D = 0.791$ (corresponding to $V_s = 10V$):

$$L_{\text{min}} = \frac{0.791 \cdot (1 - 0.791)^2 \cdot 24}{2 \cdot 10,000} \approx 41.46\,\mu H \tag{10}$$

Chosen $L = 42\,\mu H$.

Capacitor (C): For $D = 0.791$ with ripple $\Delta V_o/V_o \leq 1\%$:

$$C \geq \frac{0.791}{24 \cdot 10,000 \cdot 0.01} \approx 329\,\mu F \tag{11}$$

Chosen $C = 300\,\mu F$.

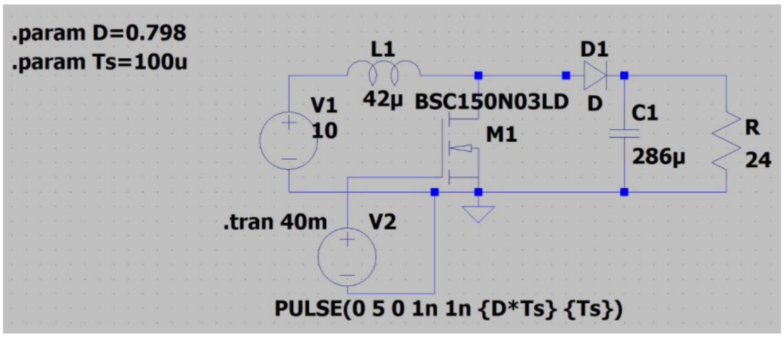

Figure 1: circuit simulation of 15V boost converter

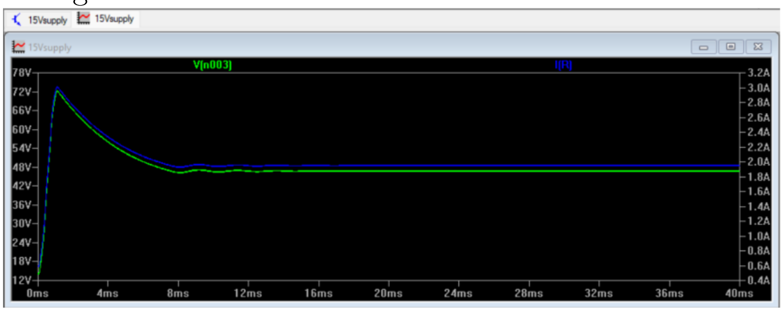

Figure 2: output of the simulation of the circuit

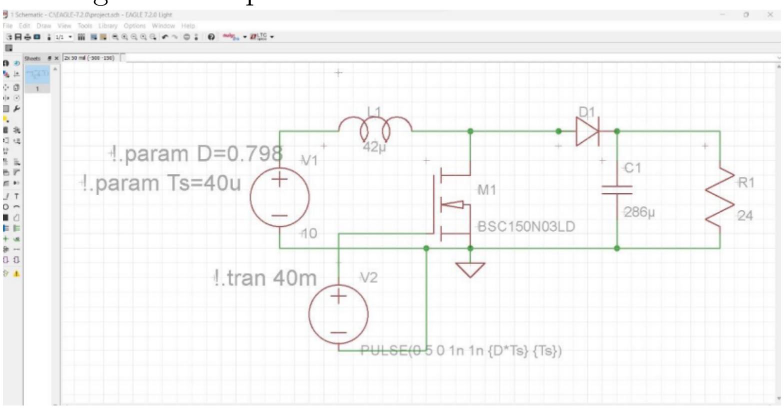

Figure 3: PCB Schematics

Simulation Results

- Stable output voltage ($V_o = 48V$).
- Key waveforms:
  - Inductor current (i_L): Linear increase and decrease.
  - Capacitor voltage (v_C): Smooth and stable.
  - Diode current (i_D): Pulsed, indicating energy transfer during the off state.

4 Applications

Boost converters are used in various fields:

- **Renewable Energy**: Stepping up solar panel output for battery charging.
- **LED Drivers**: Providing stable voltage for LED arrays.
- **Portable Electronics**: Efficient voltage regulation for laptops and smartphones.
- **Automotive Systems**: Voltage step-up for hybrid and electric vehicles.

5 Practical Considerations

- **Efficiency Losses**: Real-world converters face resistive losses, switching losses, and parasitics, reducing efficiency. Proper design minimizes these effects.
- **Switching Frequency**: Higher frequencies reduce component sizes but increase switching losses and heat.
- **Ripple Minimization**: Inductor and capacitor selection significantly impact ripple and overall stability.

Conclusion

The design and simulation of a boost converter highlight its vital role in stepping up DC voltage with high efficiency. With careful component selection and thorough understanding of its principles, boost converters can be optimized for diverse applications.

Calculations

Specifications

- **Input Voltage** (V_s): $10\,\mathrm{V} - 15\,\mathrm{V}$
- **Output Voltage** (V_o): $48\,\mathrm{V}$
- **Output Power** (P_o): $0\,\mathrm{W} - 100\,\mathrm{W}$
- **Switching Frequency** (f_s): $10\,\mathrm{kHz}$
- **Voltage Ripple** ($\Delta V_o/V_o$): $\leq 1\%$

1. Duty Cycle Calculation

The duty cycle (D) determines how much the switch is on during each switching cycle and is calculated using the output voltage formula:

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

Rearranging for D:

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

For $V_s = 10\,\mathrm{V}$:

$$D = 1 - \frac{10}{48} = 1 - 0.208 = 0.791$$

For $V_s = 15\,\mathrm{V}$:

$$D = 1 - \frac{15}{48} = 1 - 0.3125 = 0.687$$

2. Load Resistance

The load resistance (R) is calculated from the output power (P_o) and output voltage (V_o):

$$P_o = \frac{V_o^2}{R}$$

Rearranging for R:

$$R = \frac{V_o^2}{P_o}$$

At Maximum Output Power ($P_o = 100\,\mathbf{W}$):

$$R = \frac{48^2}{100} = \frac{2304}{100} = 23.04\,\Omega$$

Chosen $R = 24\,\Omega$ for simulation.

3. Inductor Calculation

The minimum inductance ($L_{\min}$) for continuous conduction mode (CCM) is:

$$L_{\min} = \frac{D \cdot (1-D)^2 \cdot R}{2 \cdot f_s}$$

For $D = 0.791$ and $R = 24\,\Omega$:

$$L_{\min} = \frac{0.791 \cdot (1-0.791)^2 \cdot 24}{2 \cdot 10,000}$$

$$L_{\min} = \frac{0.791 \cdot (0.209)^2 \cdot 24}{20,000}$$

$$L_{\min} = \frac{0.791 \cdot 0.0437 \cdot 24}{20,000} = \frac{0.829}{20,000}$$

$$L_{\min} \approx 41.46\,\mu H$$

For $D = 0.687$:

$$L_{\min} = \frac{0.687 \cdot (1-0.687)^2 \cdot 24}{2 \cdot 10,000}$$

$$L_{\min} = \frac{0.687 \cdot (0.313)^2 \cdot 24}{20,000}$$

$$L_{\min} = \frac{0.687 \cdot 0.098 \cdot 24}{20,000} = \frac{1.617}{20,000}$$

$$L_{\min} \approx 80.76\,\mu H$$

Chosen Inductor: $L = 42\,\mu H$ (close to the required value for the most demanding scenario).

4. Capacitor Calculation

The capacitance required to limit the output voltage ripple (ΔV_o) is:

$$C \geq \frac{D}{R \cdot f_s \cdot (\Delta V_o / V_o)}$$

$\Delta V_o / V_o = 1\% = 0.01$
For $D = 0.791,\ R = 24\,\Omega$**:**

$$C \geq \frac{0.791}{24 \cdot 10,000 \cdot 0.01}$$

$$C \geq \frac{0.791}{2.4} = 329\,\mu F$$

For $D = 0.687$**:**

$$C \geq \frac{0.687}{24 \cdot 10,000 \cdot 0.01}$$

$$C \geq \frac{0.687}{2.4} = 286\,\mu F$$

Chosen Capacitor: $C = 300\,\mu F$.

5. Input-Output Current Relationship

From the power balance equation:

$$V_s \cdot I_s = V_o \cdot I_o$$

Rearranging for input current (I_s):

$$I_s = \frac{V_o \cdot I_o}{V_s}$$

For $V_o = 48\,\mathbf{V},\ P_o = 100\,\mathbf{W}$**:**

$$I_o = \frac{P_o}{V_o} = \frac{100}{48} \approx 2.083\,\mathrm{A}$$

For $V_s = 10\,\mathbf{V}$**:**

$$I_s = \frac{48 \cdot 2.083}{10} \approx 10.0\,\mathrm{A}$$

For $V_s = 15\,\mathbf{V}$**:**

$$I_s = \frac{48 \cdot 2.083}{15} \approx 6.67\,\mathrm{A}$$

Summary of Calculations

Parameter	**Value (10V Input)**	**Value (15V Input)**
Duty Cycle (D)	0.791	0.687
Load Resistance (R)	$24\,\Omega$	$24\,\Omega$
Inductance (L_{min})	$41.46\,\mu H$	$80.76\,\mu H$
Capacitance (C)	$329\,\mu F$	$286\,\mu F$
Input Current (I_s)	10.0 A	6.67 A

Table 1: Summary of Calculations