ELG3336
Power Electronics

Switching-Mode Power Supply (SMPS)
Switching-Mode Buck Converter Design
Example: Computer Power Supply

120V, 60Hz ac
ac/dc converter (rectifier)

controller

dc/dc converter

12V dc
5V dc
5V dc
Example: Adjustable Motor Speed Drive

3 phase 60Hz ac

ac/dc converter (rectifier)

dc/ac converter (inverter)

DSP based control

Motor

currents

position
DC-DC Conversion: To efficiently Reduce DC Voltage

Lossless objective: \( P_{in} = P_{out} \), which means that \( V_{in}I_{in} = V_{out}I_{out} \)

\[
\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}}
\]
DC–DC Converter: Non-Efficient Way!

Linear regulator is a type of power supply which instead of using switches, employs voltage divider network for adjusting output voltage.

\[ V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \]

\[ \eta = \frac{R_2}{R_1 + R_2} = \frac{V_{out}}{V_{in}} \]

If \( V_{in} = 39V \), and \( V_{out} = 13V \), efficiency \( \eta \) is only 33%!
Another Technique: Lossless Conversion

Switch state, Load voltage
- Closed, 39 V
- Open, 0 V
Buck (Step Down) Converter in Brief

- Step down converter
- Switch
- Low-pass LC filter
- Diode
- Transition Between
  - Continuous conduction
  - Discontinuous conduction
Examples of DC Conversion

Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and **burns out the switch**.

Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor’s current momentum and resulting $Ldi/dt$ **burns out the switch**.

By adding a “free wheeling” diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.
Buck Converter Circuit
The circuit of SMPS Buck converter consists of two main parts: power stage and control stage.

Area of current research

Usually MOSFET

LPF
Buck Converter with Feedback Loop

\[ E = \frac{1}{2} L I^2 \]

\[ D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} = f_{sw} \cdot t_{on} \]
Power Loss and Efficiency of Buck Converter

\[ P_{loss} = P_{con} + P_{sw} \]

\[ P_{loss_{HS}} = \frac{R_{DS(on)} \cdot I_{out}^2 \cdot D}{P_{con}} + \frac{(V_{in} \cdot I_{out})}{2} \left( t_r + t_f \right) \cdot f_{sw} + C_{oss} \cdot f_{sw} \cdot V_{in}^2 \]

\[ P_{loss_{LS}} = R_{DS(on)} \cdot I_{out}^2 \cdot (1 - D) \]

Where \( R_{DS(on)} \) is the MOSFET drain-source on-state resistance, \( I_{out} \) is the output current, \( D \) is the power switch's duty cycle, \( V_{in} \) is the input voltage, \( t_r \) is the MOSFET rise time, \( t_f \) is the MOSFET fall time, \( f_{sw} \) is the switching frequency and \( C_{oss} \) is the MOSFET output capacitance \( (C_{DS} + C_{DG}) \).
PWM Generator

The diagram illustrates the operation of a PWM (Pulse Width Modulation) generator. It consists of a comparator and an amplifier. The comparator compares the voltage $V_C$ with a ramp generator output $V_{\text{saw}}$ to produce $V_E$. The amplifier processes $V_E$ and generates the output $V_F$ (Actual $V_o$) and $V_{\text{ref}}$ (Desired $V_o$).
Duty Cycle Calculation for Buck Converter

\[
\Delta I_{\text{ON}} = \int_0^{t_{\text{ON}}} \frac{V_L}{L} \, dt = \frac{(V_{\text{in}} - V_o)}{L} \cdot t_{\text{ON}}
\]

\[
\Delta I_{\text{OFF}} = \int_0^{t_{\text{OFF}}} \frac{V_L}{L} \, dt = \frac{(-V_o)}{L} \cdot t_{\text{OFF}}
\]

It means that energy stored in inductor at the end of cycle is equal to energy which is stored at the start of cycle, so from equation

\[
\frac{(V_{\text{in}} - V_o)}{L} \cdot t_{\text{ON}} - \frac{V_o}{L} \cdot t_{\text{OFF}} = 0
\]

\[
t_{\text{ON}} = D \cdot T \\
t_{\text{OFF}} = (1 - D)T
\]

\[
D = \frac{V_o}{V_{\text{in}}}
\]
PWM Buck Converter with Current Mode Control (CMC)

Naim Safari: Design of a DC/DC buck converter for ultra-low power applications in 65nm CMOS Process
PWM Buck Converter with Voltage Mode Control (VMC)

Naim Safari: Design of a DC/DC buck converter for ultra-low power applications in 65nm CMOS Process
Buck Converter Analysis

- \( V_o = V_A = D V_{in}; \) \( D \) = switch duty ratio
- \( \Delta i_L = \frac{1}{L} (V_{in} - V_o) DT_s = \frac{1}{L} V_o (1 - D) T_s \)
- \( I_L = I_o = \frac{V_o}{R} \)
Buck (step Down) Converter

What do we learn from inductor voltage and capacitor current in the average sense?

- Assume large C so that $V_{out}$ has very low ripple
- Since $V_{out}$ has very low ripple, then assume $I_{out}$ has very low ripple

$V_{in}$

$+ v_L -$ $i_L$

$I_{out}$ $+$ $V_{out}$ $-$

$+ 0 V -$ $I_{out}$ $I_{out}$

$V_{in}$

$+0 A -$
Designing a Buck Converter

• Design Criteria
  – Calculate the required inductor
  – Calculate the output capacitor
  – Select the input capacitor
  – Select the diode
  – Choose the MOSFET
  – Calculate the converter Efficiency

• For a Buck DC-DC converter we first calculate the required inductor and output capacitor specifications. Then determine the input capacitor, diode, and MOSFET characteristics. With the selected components, we will calculate the system efficiency.
Design Criteria

• Input voltage
• Output voltage
• Output current
• Output power
• Switching frequency
• Allowed ripple voltage
• Allowed ripple current
• Minimum efficiency
• Inductor size
• Capacitor size
\[ \Delta i_L = i_L(DT) = \frac{(V_i - V_o)}{L} D.T = \frac{V_o(1 - D)}{L.f_s} \]

\[ \Delta i_{L_{\text{max}}} = \frac{V_o(1 - D_{\text{min}})}{L_{\text{min}} f_s \Delta i_{L_{\text{max}}}} \]

\[ L_{\text{min}} = \frac{V_o(1 - D_{\text{min}})}{f_s \Delta i_{L_{\text{max}}}} \]

\[ V_{C_{\text{pp}}} = \frac{\Delta Q}{C} = \frac{\Delta i_{L_{\text{max}}}}{8f_s C} \]

\[ V_{C_{\text{pp}}} = \frac{V_o(1 - D_{\text{min}})}{8LC f_s^2} \quad f_{L_C} = \frac{1}{2\pi\sqrt{LC}} \]

\[ V_{C_{\text{pp}}} = \frac{V_o(1 - D_{\text{min}})\pi^2 f_{L_C}^2}{2f_s^2} \]

\[ C_{\text{min}} = \frac{\Delta i_{L_{\text{max}}}}{8f_s V_{C_{\text{pp}}}} = \frac{V_o(1 - D_{\text{min}})}{8f_s^2 V_{C_{\text{pp}}}} \]
Designing a Buck Converter

Assume:

\[ V_{\text{in}} = 12 \text{ V} \]
\[ V_{\text{OUT}} = 5 \text{ volts} \]
\[ I_{\text{LOAD}} = 2 \text{ amps} \]
\[ F_{\text{sw}} = 400 \text{ KHz} \]
\[ D = \frac{V_{\text{in}}}{V_{\text{out}}} = \frac{5\text{V}}{12\text{V}} = 0.416 \]

Define Ripple current:

\[ I_{\text{ripple}} = 0.3 \cdot I_{\text{LOAD}} \quad \text{(typically 30\%)} \]

For an Inductor: \[ V = L \cdot \frac{\Delta I}{\Delta T} \]

Rearrange and substitute:

\[ L = (V_{\text{in}} - V_{\text{out}}) \cdot \left( \frac{D}{F_{\text{sw}}} \right) / I_{\text{ripple}} \]

Calculate:

\[ L = 7 \text{ V} \cdot \left( \frac{0.416}{400 \text{ KHz}} \right) / 0.6\text{A} \]
\[ L = 12.12 \text{ uh} \]

Select C, Diode (Schottky), and the MOSFET

Calculate the Efficiency
Example

• In **Buck** converter, \( L = 24\mu\text{F} \) (steady-state): \( V_{\text{in}} = 20\text{V} \); \( D = 0.6 \);
  \( P_{\text{o}} = 14\text{V} \); \( f_s = 200 \text{kHz} \). Calculate and draw the waveform.