Reducing Emissions in DC-DC Switched Mode Power Supplies

Scott Mee – Johnson Controls
Jim Teune – Gentex
Outline

- Overview of SMPS designs and basic emissions issues
- Root Causes of Emissions
- Design Strategies for Reducing Emissions
  - Schematic Design
  - Component Selection
  - Layout Considerations
- Trade-offs between EMI and other requirements
- Hardware Demonstration
Power Supplies
Linear vs. switching

Linear supplies
- Typically used when the input and output voltage levels are similar
- Large voltage drops and high current output cause low efficiency
- Low efficiency = higher heat
- Quiet from RF emissions point of view

Switching supplies
- Preferred for applications where efficiency is important
- Buck → step down → i.e. 12Volts to 5Volts logic level
- Boost → step up → i.e. 12Volts to 40Volts LED lighting level
- Sudden changes in voltage & current cause EMC problems
- Circuit uses a switch, inductor and diode to transfer energy from input to output
Buck SMPS

\[ V_{out} = V_{IN} \times D, \text{ where } D = \frac{t_{ON}}{t_{ON} + t_{OFF}} \]
Buck SMPS

Charge phase

---

V

S

L

D

C

R

---

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Buck SMPS

Discharge phase
Buck Circuit Voltages and Currents

Switch State

Vin
Vout
Vind
0 volts

I_{min}
I_{max}
Boost SMPS

\[ V_{out} = \frac{V_{IN}}{1 - D}, \quad \text{where} \quad D = \frac{t_{ON}}{t_{ON} + t_{OFF}} \]
Boost SMPS

Charge phase
Boost SMPS

Discharge phase
Boost Circuit Switching Voltages and Currents

Switch State

I_{ind}

I_{diode}

Vin

Vout

V_{ind}

V_{out}

0 volts

Timing

Vin

V_{ind}

V_{out}

0 volts
Trapezoidal Periodic Signals

\[ x(t) = c_0 + \sum_{n=1}^{\infty} 2|c_n| \cos(n \omega_0 t + \angle c_n) \]

\[ c_n = A \frac{T}{\tau} \frac{\sin\left(\frac{1}{2} n \omega_0 \tau\right)}{\frac{1}{2} n \omega_0 \tau} \frac{\sin\left(\frac{1}{2} n \omega_0 \tau_f\right)}{\frac{1}{2} n \omega_0 \tau_f} e^{-j n \omega_0 (\tau + \tau_f)/2}, \quad \tau_f = \tau_r \]

\[ c_0 = A \frac{T}{\tau}, \quad \tau_r = \tau_f \]
Bandwidth of Periodic Waveforms

Above the 2nd break point, the harmonics drop off at a rate of -40dB/decade.

To be conservative we might choose a point, 3 times this second breakpoint this is approximately

$$BW = \frac{1}{\pi \tau_r} \text{ Hz}$$
Noise Sources in SMPS

- Switching characteristics
  - \(\frac{dv}{dt}\) & \(\frac{di}{dt}\)
  - Fundamental frequency
  - Harmonic series

- Resonances
  - Step response to the RLC network → Ringing

- Secondary effects
  - Power surges at input
  - Ripple on power bus
  - Ripple on system wiring
  - Output ripple
  - Magnetic fields
BUCK Supply Emissions Investigation
Emissions Investigation
BUCK SMPS Circuit
Emissions Investigation

BUCK Voltage Measurements

Voltage at Input to SMPS

Switch Output Voltage

Ch2 Mean
-5.561mV

Ch2 Pk–Pk
340.1mV

3 Oct 2001
13:40:33
Emissions Investigation
BUCK Voltage Measurements – Zoom

Voltage at Input to SMPS

Switch Output Voltage
Emissions Investigation
Narrow Band vs. Broadband

Time domain

Frequency domain

CH1 

max
mean
min

13.44V
-?
-?

pkpk
15.23V
freq
270.4kHz

-1.3V DC

TRIGGER ON CH1

CH1 MEASUREMENTS

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Conducted Emissions (150kHz – 2MHz)

Before Techniques Applied

After Techniques Applied

Improvement came from
- Front-end filtering (L/C filter)
- Slew rate controls
- Layout improvements
Emissions Investigation

Success Stories – 150kHz SMPS (Low band)

Conducted Emissions (150kHz – 2MHz)

Improvement came from
- Front-end filtering (L/C filter)
- Layout improvements
Emissions Investigation
Success Stories – 150kHz SMPS (High band)

CISPR 25 – Radiated Emissions (25MHz – 200MHz)

Improvement came from
- Diode snubber
- Diode switching changes
- Layout improvements

Before Techniques Applied

After Techniques Applied
BOOST Supply
Emissions
Investigation
Emissions Investigation
Boost Supply Case Study

- 12volt input & 34volt output

+12 V

+34 V
Emissions Investigation
Boost Supply – current loop when switch is closed

- Red = current flow to load, Blue = return current

+12 V +34 V
Emissions Investigation

Boost Supply – current loop when switch is open

- Red = current flow to load, Blue = return current

+12 V +34 V

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Johnson Controls
Emissions Investigation
Boost Supply → Radiated Emissions 50MHz – 180MHz BL ON

123MHz
161MHz
Emissions Investigation
Boost Supply ➔ Radiated Emissions 50MHz – 180MHz BL OFF
Emissions Investigation
Boost Supply → Measurement points

+12 V

+34 V
Emissions Investigation
Boost Supply → Measurement Setup

- Bench measurement setup overview

LeCroy 6GHz 40GS/s
- Voltage probe
  500MHz 1.8pf
- Current probe Langer
  HF magnetic field probe
Emissions Investigation
Boost Supply → Measurement Setup

- Bench measurement setup overview

- Voltage probe used to show when switch is open/closed

- Current probe used to see shape of current flowing through the diode
Emissions Investigation

Boost Supply → Voltage Measurement Results

- Overview of switching waveforms

![Waveform Diagram]
Emissions Investigation
Boost Supply → Voltage Measurement Results

- Switch turns from off to on

![Graph showing voltage and current changes during switch turn-on](image-url)
Emissions Investigation

Boost Supply \rightarrow Voltage Measurement Results

- Switch turns from on to off

![Graph showing voltage and current measurements](image-url)
Emissions Investigation
Boost Supply → Radiated Emissions 50MHz – 180MHz BL ON

123MHz

161MHz
Emissions Investigation

Boost Supply → Diode Current → No changes / Baseline

- 123MHz ringing corresponds to 123MHz emissions

123MHz
Emissions Investigation
Boost Supply → Diode Current → 1nf cap across diode CR6401

- 77 MHz ringing corresponds to 77MHz emissions
Schematic Design
Schematic Design

Buck topology

- 12V input
- 5V output

+12 V

Input filtering

Soft-start capacitor

Slew rate control

Snubber

Output filter

+5 V

Spread spectrum
Schematic Design

Boost topology

Front end Pi filter

Slew rate control

Snubber

Output cap

GND loop must be as small as possible
Schematic Design
Snubber Calculations

\[ F_{\text{Ringing}} := 126 \text{MHz} \]

\[ C_{\text{Snubber}} := 1500 \text{pF} \]

\[ F_{\text{Tuned}} := 40 \text{MHz} \]

\[ C_{\text{Parasitic}} = 168.114 \text{pF} \]

\[ L_{\text{Parasitic}} = 9.491 \times 10^{-9} \text{H} \]

The optimum resistor to damp the overshoot is twice the inductive impedance at the new resonant frequency. This is calculated by the following equation:

\[ R_{\text{Snubber}} := 2 \left( \frac{2\pi F_{\text{Tuned}} L_{\text{Parasitic}}}{C_{\text{Snubber}}} \right) \]

\[ R_{\text{Snubber}} = 4.771 \Omega \]

\[ C_{\text{Snubber}} = 1.5 \times 10^{-9} \text{F} \]
Component Selection
Component Behavior

Capacitors, Resistors, Inductances, Ferrites

- All passive components have resistance, capacitance and inductance
- Component behavior is different at low and high frequencies
Component Behavior
Ceramic Capacitors

ESL - Equivalent Series Inductance (L)

Capacitor has low impedance for a narrow range of frequencies

\[ f_{\text{res}} = \frac{1}{2 \pi \sqrt{L_{\text{lead}} C}} \]
Component Behavior
Electrolytic Capacitors – Example → 150uf 10V

- Power supply output filter

![Diagram of power supply output filter]

**Aluminum Electrolytic Capacitors**

**CE-EX Series**
- Low ESR at High Frequency

**Specifications**

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage (V)</td>
<td>4</td>
</tr>
<tr>
<td>Surge voltage (V)</td>
<td>4.6</td>
</tr>
<tr>
<td>Capacitor temperature range (°C)</td>
<td>-55 to 105°</td>
</tr>
<tr>
<td>Capacitance tolerance (%)</td>
<td>±20</td>
</tr>
<tr>
<td>Tariff of the angle (MAX)</td>
<td>0.22</td>
</tr>
<tr>
<td>Leakage current (µA)</td>
<td>The greater of either 0.1µA or 50µA</td>
</tr>
<tr>
<td>Temperature characteristic impedance ratio at 120Hz</td>
<td>Z=</td>
</tr>
<tr>
<td>Endurance</td>
<td>Test</td>
</tr>
<tr>
<td>105°C</td>
<td>±6.3: 2000hrs, ±6.6: 1000hrs, (±10%: 5000hrs)</td>
</tr>
<tr>
<td>Rated voltage applied</td>
<td>±6.3</td>
</tr>
<tr>
<td>Leakage current (µA)</td>
<td>Within ±30% of the initial value</td>
</tr>
<tr>
<td>Capacitance (µF)</td>
<td>±20</td>
</tr>
</tbody>
</table>

What does this mean???
Component Behavior
Electrolytic Capacitors – Example ➔ 150uf 10V

- Capacitance measurement over frequency
  - HP4284A Precision LCR Meter & 16047D adapter used
Component Behavior
Electrolytic Capacitors – Example ➔ 150μF 10V

No real capacitance after a few kHz

Long Wave Band
Medium Wave Band

SUNCON 150μF 20% 10V

Capacitance (μF)

Frequency (Hz)
Component Behavior

Inductors

Inductance resonates with parasitic capacitance between windings of the inductor

Saturation can happen

\[ f_{res} = \frac{1}{2\pi \sqrt{LC_{par}}} \]
Component Behavior

Inductors

**Resonant Frequency**

Impedance $|Z| \text{ versus frequency } f$

measured with impedance analyzer

Agilent 4294A, typical values at 20 °C

- 10uH goes resonant at 30MHz
- 10uH has only ~180ohms impedance at 300kHz

**Saturation Curves**

Inductance $L \text{ versus DC load current } I_{DC}$

measured with LCR meter Agilent 4275A,

typical values at 20 °C

10uH goes resonant at 30MHz

Our typical use cases are borderline saturation
### Component Behavior

**Inductors**

- **Low profile is very important!**

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Number</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQH44 Murata</td>
<td>1.1mm</td>
<td>✔</td>
</tr>
<tr>
<td>Vishay IHLP-2020BZ</td>
<td>2 mm</td>
<td>✔</td>
</tr>
<tr>
<td>Vishay IHLP-4040DZ</td>
<td>4 mm</td>
<td>✔</td>
</tr>
<tr>
<td>EPCOS B82472P6</td>
<td>4.5mm</td>
<td>✔</td>
</tr>
<tr>
<td>EPCOS B82477P4</td>
<td>8.5mm</td>
<td>✗</td>
</tr>
</tbody>
</table>

- **Shorter package → flux lines stay closer to the board → lower emissions**
Component Behavior
Resistor

Resistors are not purely resistive as frequency increases

\[
f_{\text{res}} = \frac{1}{2\pi \sqrt{L_{\text{lead}} C_{\text{par}}}}
\]
Component Behavior

Diodes

Schottkey
Soft start
Slow start
Fast start
Efficiency vs. heat vs. di/dt for emissions

I-V graph of a real diode
Component Behavior

Ferrite bead

- *Do not trust the curves you see in the datasheet!!!*
- Be sure to understand the circuit where the ferrite will be used
- Impedance over frequency graphs change with DC bias
Component Behavior
Ferrite bead

- Take care when choosing a ferrite by its rating
- Ratings are typically done at 100MHz
Layout Design
Buck Power Supply
Layout – Component Placement
Buck Power Supply
Layout – Copper Definitions

- **GND**
- **PWR**
Buck Power Supply
Layout – Switch Closed

- Start by drawing the path of the current
- Ensure area of loop formed by current is kept small
- Keep high di/dt components on same side of PCB
- Allow common ground between input cap, regulator, diode, snubber and output cap
- Keep snubber next to diode
- Inductor GND: to fill or not to fill? (efficiency vs. EMC)
Don’t forget there are two switch states!
Boost Power Supply
Schematic
Boost Power Supply
Component Placement

- Same as BUCK supply with these additional items:
  - Keep switch node away from surrounding copper areas
  - Make switch node as small as possible
  - Inductor orientation/wiring makes a difference (node connected to winding on inside or outside)
Boost Power Supply

PCB Layout

- Keep switch node small
- Maintain spacing to surrounding copper areas

\[ C_A := \varepsilon \cdot \frac{A}{D} \quad \rightarrow \quad 1.72\text{pF} \]
Avoid SMPS loop within a GND loop → provide continuous ground fill

\[ L_{\text{mut}} = N^2 \frac{\mu_0 \mu_I}{\pi} \left[ -2(w + h) + 2 \sqrt{h^2 + w^2} - \hbar \ln \left( \frac{h + \sqrt{h^2 + w^2}}{w} \right) - \omega \ln \left( \frac{w + \sqrt{h^2 + w^2}}{h} \right) + \omega \hbar \ln \left( \frac{2h}{\alpha} \right) + w \omega \ln \left( \frac{2w}{\alpha} \right) \right] \]

- L1 = 50nH
- L2 = 270nH
- K = 0.45 (represents poor coupling between loops; where 1 = perfect coupling)

- Lm = 52nH → mutual inductance between loops
Design Trade-Offs
Recommendations for a Balanced Design

- Thermal constraints prefer faster switching, larger copper areas and spacing
- EMC constraints prefer slow switching, smaller copper and spacing

Thermal Constraints →

EMC Constraints →

Common Solution →
Recommended Reading

Power Electronics Technology trade magazine (www.powerelectronics.com)
http://www.ridleyengineering.com/


Texas Instruments Application Report SLPA005, “Reducing Ringing Through PCB Layout Techniques”

Demystifying Switching Power Supplies by Raymond A. Mack
Thank you for your attention

Questions?
Hardware Demonstration
Hardware Demonstration

2012 Student EMC Hardware Design Competition

Switched-Mode Power Supply
Hardware Demonstration – Buck SMPS

Base unit (no EMC components)  Fully populated PCB