Decoupling and Filtering Applications
Decoupling and Filtering
Microprocessor Block Diagram

Decoupling: Gives Something Up

Filtering: Passes Something Along

DC Input
>12V
DC to DC (12V)
5V
VRM (3.3V)
3.3V
IC
Decoupling
Decoupling

Introduction

IC

I need some charge!

Charge coming up!

“Bypass” Capacitor

- Eliminate High-Frequency Noise
- Decouple RC Delays
- Prevent Voltage Droop

Power Supply
Decoupling Principles
Cascading Capacitors

Cascaded same capacitors in parallel:
- Broader Low Impedance Bandwidth
- Reduction of ESR
- Lower Physical Inductance

\[
\text{Freq} = \frac{1}{2\sqrt{\frac{ESL}{nC}}}
\]
Decoupling Principles
Cascading Capacitors

Cascaded different capacitors in parallel:
- Much Broader Low Impedance Bandwidth
- Reduction of ESR
- Lower Physical Inductance

Resultant impedance curve, (combined impedances of all decoupling capacitors).

\[ Z_{\text{Target}} = \frac{V_{\text{Rail}} \cdot \% \text{Ripple}}{100} \div I_{\text{Max, Transient}} \]
Calculating Target Impedance

- Needed for $Z_{\text{Target}}$
  - Max transient current
  - Rail voltage
  - Max AC ripple (% of supply)
  - $f_{\text{Target}}$ is max switching frequency

$$Z_{\text{Target}} = \frac{V_{\text{Rail}} \times \% \text{Ripple}}{100 \div I_{\text{MaxTransient}}}$$

Determine Z of PDN → Transform Z Spectrum into Time Domain → Integrate Transform → Subtract Step Response from VRM

http://www.electrical-integrity.com/

What is the combined impedance of multiple parts in parallel?
Filtering
Filtering
Introduction

Blocking of unwanted signals

Noise Filter

Passing of wanted signals

Low Pass Filter
**Filtering Principles**

*Example: DC to DC Converter*

<table>
<thead>
<tr>
<th>Capacitors</th>
<th>Frequency</th>
<th>$V_{in} &gt; 40V$</th>
<th>$V_{in} &lt; 40$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>Mid to High</td>
<td>Good</td>
<td>Good, Low-Cost</td>
</tr>
<tr>
<td>Film</td>
<td>Mid</td>
<td>Good</td>
<td>Not Ideal</td>
</tr>
<tr>
<td>Aluminum Electrolytic</td>
<td>Low</td>
<td>Good, Low-Cost</td>
<td>Good, Low-Cost</td>
</tr>
<tr>
<td>Aluminum V-Chip Polymer</td>
<td>Low to Mid</td>
<td>Good, Low-Cost</td>
<td>Good, Low-Cost</td>
</tr>
<tr>
<td>Polymer</td>
<td>Mid</td>
<td>Acceptable</td>
<td>Good</td>
</tr>
<tr>
<td>Tantalum MnO₂</td>
<td>Low</td>
<td>Poor</td>
<td>Good</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inductors</th>
<th>Current</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Composite</td>
<td>Up to 40A</td>
<td>Soft</td>
</tr>
<tr>
<td>Ferrite</td>
<td>Up to 70A</td>
<td>Hard</td>
</tr>
</tbody>
</table>
Example Input Filter

2.78\(V_{\text{PP}}\) without filtering

0.47\(V_{\text{PP}}\) with filtering

\[ V_{\text{IN}} = 10V, V_{\text{OUT}} = 30V, I_{\text{OUT}} = 3A \]

W/O Input Filter: Short L2 and L3, Remove Cm2

V\text{IN} \text{ Peak-to-Peak Ripple} = 2.78V

W Input Filter: Stuff L2, L3 and Cm2

V\text{IN} \text{ Peak-to-Peak Ripple} = 0.47V
Decoupling and Filtering
Example: Power Distribution System

Simplified Power Distribution Network

Input Caps to Decouple Near Each Converter

Simplified DC to DC Converter

Processor Core (VID)
Processor IO, Platform Controller (PCH)
Memory Controller, PCH
Graphics, PCH
Display, PCH ...

Output Caps to Filter on Each Converter

DC to DC Converter
2 – 4 Phases

DC to DC Converter

DC to DC Converter

DC to DC Converter

DC to DC Converter

DC to DC Converter

Processor Core (VID)
Processor IO, Platform Controller (PCH)
Memory Controller, PCH
Graphics, PCH
Display, PCH ...

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Filtering / Decoupling Choices
Choosing from KEMET

“High” ESR Electrolytics
• Filters low frequency noise
• Act as charge reservoirs to transient currents

Low ESR Electrolytics

Low ESL Ceramics
• Low inductance (ESL) and low ESR parts provide high frequency decoupling
Load Transient
Load Transient
Inductor Calculation

\[ L_{out} = \frac{[V_{out} \times (V_{in} - V_{out})]}{\Delta I_L \times f_s \times V_{in}} \]

- \( V_{in} \) = Typical input voltage
- \( V_{out} \) = Desired output voltage
- \( f_s \) = Minimum switching frequency of the converter
- \( \Delta I_L \) = Estimated inductor ripple current
  = (0.2 to 0.4) \( I_{OUT(max)} \)

Buck: \( V_{out} < V_{in} \)
Load Transient
Inductor Calculation

Vin = 12V
Vout = 1.2V
fs = 600 kHz
ΔIL = (0.2 to 0.4) x 300A = 60A to 120A

Controller

Vout
Load

Buck: Vout < Vin

\[ L_{out} = \frac{[1.2V \times (12V - 1.2V)]}{120A \times 600kHz \times 12V} = 15nH \]

\[ L_{out} = \frac{[1.2V \times (12V - 1.2V)]}{60A \times 600kHz \times 12V} = 30nH \]
Load Transient Capacitor Calculation

$C_{\text{outmin}} = \frac{L \times I_{\text{step}}^2}{2 \times V_{\text{outuv}} \times D_{\text{min}} \times (V_{\text{inmax}} - V_{\text{out}})}$

- $C_{\text{outmin}}$ – Minimum required output capacitance in uF
- $L$ – Output inductance in uH
- $I_{\text{step}}$ – Transient current change from high load to minimum load in A
- $V_{\text{outuv}}$ – Output voltage regulation in mV
- $D_{\text{min}}$ – Duty cycle – $V_{\text{out}} / V_{\text{inmax}}$
- $V_{\text{inmax}}$ – Maximum input voltage in V
- $V_{\text{out}}$ – Output voltage in V

Buck: $V_{\text{out}} < V_{\text{in}}$
Load Transient
Capacitor Calculation

\[ C_{out\text{min}} = \frac{15nH \times 290A^2}{2 \times 50mV \times 0.111 \times (12V - 1.2V)} = 10.5mF \]

- \( L = 15.0nH \)
- \( I_{\text{step}} = 290A \)
- \( V_{\text{out}_{uv}} = 50mV \)
- \( D_{\text{min}} = 0.111 \)
- \( V_{\text{in}_{\text{max}}} = 12V \)
- \( V_{\text{out}} = 1.2V \)
Load Transient Example Including ESR
470uF, 2.5VDC, 5mΩ Capacitor
Load Transient
Capacitor Calculation with ESR Added

\[ C_{outmin} = \frac{L \times I^2_{step}}{2 \times (V_{out_{uv}} - V_{dropESR}) \times D_{min} \times (V_{in_{max}} - V_{out})} \]

- \( C_{outmin} \) – Minimum required output capacitance in \( \mu F \)
- \( L \) – Output inductance in \( \mu H \)
- \( I_{step} \) – Transient current change from high load to minimum load in \( A \)
- \( V_{out_{uv}} \) – Output voltage regulation in \( mV \)
- \( V_{dropESR} \) – Voltage drop across the resistive component of the output capacitor in \( mV \)
- \( D_{min} \) – Duty cycle – \( V_{out} / V_{in_{max}} \)
- \( V_{in_{max}} \) – Maximum input voltage in \( V \)
- \( V_{out} \) – Output voltage in \( V \)
Load Transient
Capacitor Calculation with ESR Added

Three Unknowns
1. $C_{\text{outmin}}$
2. $V_{\text{dropESR}}$
3. $n_c$

$$C_{\text{outmin}} = \frac{L \times I_{\text{step}}^2}{2 \times (V_{\text{outuv}} - V_{\text{dropESR}}) \times D_{\text{min}} \times (V_{\text{inmax}} - V_{\text{out}})}$$

$$V_{\text{dropESR}} = 2 \times \left( \frac{ESR_c}{n_c} \right) \times I_{\text{step}}$$

$$n_c = \frac{C_{\text{outmin}}}{C_{\text{eff/\text{cap}}}}$$
Load Transient
Capacitor Calculation with ESR Added

- \(L = 15.0\, \text{nH}\)
- \(I_{\text{step}} = 290\, \text{A}\)
- \(V_{\text{out}_{uv}} = 50\, \text{mV}\)
- \(D_{\text{min}} = 0.111\)
- \(V_{\text{in}_{\max}} = 12\, \text{V}\)
- \(V_{\text{out}} = 1.2\, \text{V}\)
- \(\text{ESR}_c = 5\, \text{m}\Omega\)
- \(C_{\text{eff/cap}} = 470\, \mu\text{F}\)

\[V_{\text{dropESR}} = 2 \times \left(\frac{5\, \text{m}\Omega}{n_c}\right) \times 290\, \text{A}\]

\[C_{\text{out}_{\min}} = \frac{15\, \text{nH} \times (290\, \text{A})^2}{2 \times (50\, \text{mV} - V_{\text{dropESR}}) \times 0.111 \times (12\, \text{V} - 1.2\, \text{V})}\]

\[n_c = C_{\text{out}_{\min}} / 470\, \mu\text{F}\]
Load Transient
Capacitor Calculation with ESR Added

- L – 15.0nH
- \( I_{\text{step}} \) – 290A
- \( V_{\text{out}_{uv}} \) – 50mV
- \( D_{\text{min}} \) – 0.111
- \( V_{\text{in}_{\text{max}}} \) – 12V
- Vout – 1.2V
- \( ESR_c \) – 5mΩ
- \( C_{\text{eff/cap}} \) – 470uF

\[
C_{\text{out}_{\text{min}}} = \frac{15nH \times 290A^2}{2 \times (50mV - (2 \times \left(\frac{5mΩ}{C_{\text{out}_{\text{min}}} / 470uF}\right) \times 290A)) \times 0.111 \times (12V - 1.2V)}
\]

**Taking ESR into Consideration**

\[
C_{\text{out}_{\text{min}}} = 37.783mF \rightarrow n_c = 81 \text{ capacitors}
\]

**Not Taking ESR into Consideration**

\[
C_{\text{out}_{\text{min}}} = 10.5mF \rightarrow n_c = 23 \text{ capacitors}
\]
Load Transient Example
470uF, 2VDC, 3mΩ Capacitor
Load Transient
 Capacitor Calculation with ESR Added

$$C_{\text{outmin}} = \frac{L \times I_{\text{step}}^2}{2 \times (V_{\text{outuv}} - V_{\text{dropESR}}) \times D_{\text{min}} \times (V_{\text{inmax}} - V_{\text{out}})}$$

- $C_{\text{outmin}}$ – Minimum required output capacitance in uF
- $L$ – Output inductance in uH
- $I_{\text{step}}$ – Transient current change from high load to minimum load in A
- $V_{\text{outuv}}$ – Output voltage regulation in mV
- $V_{\text{dropESR}}$ – Voltage drop across the resistive component of the output capacitor in mV
- $D_{\text{min}}$ – Duty cycle – $V_{\text{out}} / V_{\text{inmax}}$
- $V_{\text{inmax}}$ – Maximum input voltage in V
- $V_{\text{out}}$ – Output voltage in V

Vin

Controller

ESR

Load

Buck: Vout<Vin

Vout
Load Transient
Capacitor Calculation with ESR Added

Three Unknowns
1. $C_{outmin}$
2. $V_{dropESR}$
3. $n_c$

\[
C_{outmin} = \frac{L \times I_{step}^2}{2 \times (V_{outuv} - V_{dropESR}) \times D_{min} \times (Vin_{max} - V_{out})}
\]

\[
V_{dropESR} = 2 \times \left( \frac{ESR_c}{n_c} \right) \times I_{step}
\]

$n_c = \frac{C_{outmin}}{C_{eff/cap}}$
Load Transient
Capacitor Calculation with ESR Added

- \( L = 15.0 \text{nH} \)
- \( I_{\text{step}} = 290 \text{A} \)
- \( V_{\text{out}_{\text{uv}}} = 50 \text{mV} \)
- \( D_{\text{min}} = 0.111 \)
- \( V_{\text{in}_{\text{max}}} = 12 \text{V} \)
- \( V_{\text{out}} = 1.2 \text{V} \)
- \( ESR_c = 3 \text{m}\Omega \)
- \( C_{\text{eff/cap}} = 470 \text{uF} \)

\[
C_{\text{outmin}} = \frac{15nH \times 290A^2}{2 \times (50mV - V_{\text{dropESR}}) \times 0.111 \times (12V - 1.2V)}
\]

\[
V_{\text{dropESR}} = 2 \times \left( \frac{3\text{m}\Omega}{n_c} \right) \times 290A
\]

\[
n_c = \frac{C_{\text{outmin}}}{470\text{uF}}
\]

THREE UNKNOWNS
Load Transient
Capacitor Calculation with ESR Added

- \(L = 15.0\text{nH}\)
- \(I_{\text{step}} = 290\text{A}\)
- \(V_{\text{out}_{uv}} = 50\text{mV}\)
- \(D_{\text{min}} = 0.111\)
- \(V_{\text{in}_{\text{max}}} = 12\text{V}\)
- \(V_{\text{out}} = 1.2\text{V}\)
- \(\text{ESR}_c = 3\text{m}\Omega\)
- \(C_{\text{eff/cap}} = 470\text{uF}\)

Taking Lower ESR into Consideration
\[
C_{\text{out}_{\text{min}}} = 26.879\text{mF} \rightarrow n_c = 58 \text{ capacitors}
\]

Taking Higher ESR into Consideration
\[
C_{\text{out}_{\text{min}}} = 37.783\text{mF} \rightarrow n_c = 81 \text{ capacitors}
\]

Not Taking ESR into Consideration
\[
C_{\text{out}_{\text{min}}} = 10.5\text{mF} \rightarrow n_c = 23 \text{ capacitors}
\]
Thank You!