Switched Mode Power Supply with high efficiency and best EMI design

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REQUIREMENTS IN EMC
EMC - Standards

- EN 61000-3-2  Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)
- EN 61000-3-3  Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems
- EN 55011     ISM Equipment (Industrial, Scientific and Medical) also known as CISPR-11
- EN 55013     Audio and Broadcast receiver equipment
- EN 55014-1   House hold appliances, electric tools and similar apparatus
- EN 55015     Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment
- EN 55022     ITE (Information Technology Equipment), also known as CISPR-22
- EN 61000-6-1 Generic immunity standard for residential, commercial and light industry environments
- EN 61000-6-2 Generic immunity standard for industrial environments
- EN 61000-6-3 Generic emission standard for residential, commercial and light industry environments
- EN 61000-6-4 Generic emission standard for industrial environments
- EN 61000-4-2 Electrostatic discharge immunity test (ESD)
CE Marking

- With the formation of the single European market, standardization was required to remove technical barriers to trade.
- New Approach Directives were introduced to remove these barriers to trade.
- 22 New Approach Directives
  - Electro Magnetic Compatibility (EMC)
  - Low Voltage Directive (LVD)
  - Medical Devices Directive (MDD)
What is the meaning of EMC?
What’s all the fuss about EMC?

- In Europe, we have a mechanism called CE Marking

- It is applicable to any electrical/electronic product

- EMC Directive, regulation to ensure that intentional RF transmission signals are not interfered with

- Ensures that Electrical/Electronic devices continue to operate as intended in a Electro Magnetic Environment

- Failure to comply with the law can be an offence, either criminal, civil or both
Other International EMC approval marks

- Federal Communications Commission
- Voluntary Control Council for Interference
- Australian Communications and Media Authority
Conducted Emission

- Conducted emission over wideband
- Caused by ripple current at input lines (common mode - / differential mode noise)
- EMC requirements for „Conducted Emission“ according ETSI, CEN, CENELEC

- E.g.: EN 55013 : 2006 (Radio & TV broadcast receivers and associated equipment)

66 - 56dBµV @ 150<KHz<500KHz (QP)
56 - 46dBµV @ 150<KHz<500KHz (Av)

56dBµV @ 0,5<MHz<5 (QP)
46dBµV @ 0,5<MHz<5 (Av)

60dBµV @ 5<MHz<30 (QP)
50dBµV @ 5<MHz<30 (Av)
Radiated Emission

- Radiated emission over wideband
- Caused by:
  - Power traces on PCB
  - Power choke of DC/DC converter
- EMC requirements for "Radiated Emission" according ETSI, CEN, CENELEC

- **EN 61000-6-3**: 2007 (Home)
  30dB @ 30MHz~230MHz µV/m
  37dB @ 230MHz~1GHz µV/m

- **EN 61000-6-4**: 2007 (Industrial)
  40dB @ 30MHz~230MHz µV/m
  47dB @ 230MHz~1GHz µV/M
EMC – Basic Phenomena

Electromagnetic Compatibility

- Emission
  - Conducted
  - Radiated
- Immunity
  - Conducted
  - Radiated
Magnetic and Material Basics
Permeability – complex permeability

\[ Z = \sqrt{R^2 + X_L^2} \]

Core material-Parameter

Replacement circuit
Core materials - Inductors (Energy storage)

Which switching frequency do you use?

Impedance Z / %

- $X_L(\text{Fe})$
- $X_L(\text{MnZn})$
- $X_L(\text{NiZn})$

Frequency f/MHz

- 0-200kHz
- 1-10MHz
- 1-40MHz
Core materials- Chokes (filtering)

Noise frequency range must be known

Impedance $Z / \%$

- **$R (Fe)$**
- **$R (MnZn)$**
- **$R (NiZn)$**

- **200kHz-4MHz**
- **3-60MHz**
- **20-2000MHz**

Frequency $f / MHz$
Core Losses

Electro Magnetic energy cannot disappear, it will be just transformed into other energy form → energy conservation law

e.g. electrical energy transformed into → thermal energy

the core losses from ferrite transform the noise energy into heat
Core material (Inductor / EMC Ferrite)

- Compare the Q

\[ Q = \frac{X_L}{R} \]
Transmission Modes & Filter Topologies
EMC - Coupling

→ **Primary procedure**
  
  …to aim at source a low noise

→ **Secondary procedure**
  
  … eliminate the noise thru interrupting the coupling way

→ **Tertiary procedure**
  
  … increase the noise immunity at load
Recognizing the coupling mode

- common mode noise?
- differential mode noise?
Common mode or differential mode?

Take a Snap Ferrite and fix it on the cable (both lines e.g. VCC and GND)

if noise is reduced or noise immunity increase

you have Common Mode Interference

If not

you have Differential Mode Interference

e.g. Common mode choke

e.g. chip bead ferrite
Snap on ferrite – typical behavior

Increase the no. of turns means:

- Star FIX LFS
- Star TEC
- 3 turns MnZn
- 2 turns MnZn
- 1 turn MnZn
- 3 turns
- 2 turns
- 1 turn
Snap on ferrite - Construction

- Snap on ferrite acts as an CMC
- Absorbs common mode Interferences
- Comparable with bifilar winding CMC
Common Mode Filter – How it works

It is a Bi-directional filter

- From device to outside environment
- From outside environment to inside device

Intended Signal - Differential mode

Interference Signal (noise) – Common Mode

Conclusion:

- “almost” no affect the signal - Differential mode
- high attenuation to the interference signal (noise) – Common Mode
Insertion loss – Mathematical Definition

- System attenuation

\[ A = 20 \cdot \log \frac{Z_A + Z_F + Z_B}{Z_A + Z_B} \quad \text{in} \ (dB) \]

- Impedance

\[ Z_F = \left[ 10^{\frac{A}{20}} \cdot (Z_A + Z_B) \right] - (Z_A + Z_B) \quad \text{in} \ (\Omega) \]
Insertion loss - Definition

- Practical values for source and load impedances:
  - Ground planes: <1 ... 2 Ω
  - Vcc distribution: 10 ... 20 Ω
  - Video- /Clock- /Data line: 50 ... 90 Ω
  - long data lines: 90 ... >150 Ω
How to calculate the right chip beat ferrite?

Example: power supply

(1) Required insertion loss of ferrite: 22dB @ 100 MHz
(2) System impedance for power supplies: Z < 10 Ω
(3) $Z_{\text{ferrite}} = 220$ Ω
(4) 742792022
Use the WE catalog and use 749792022

220Ω>
Possibility 1: too high attenuation

→ Could be because of wrong system impedance
→ reduce the impedance of ferrite
Possibility 2: too low attenuation

→ Could be because of wrong system impedance
→ increase the impedance of ferrite (Z_F~1000Ω)
Insertion loss – recommended filter topology

Source Impedance

<table>
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<tr>
<th>low</th>
<th>high</th>
<th>high or unknown</th>
<th>low</th>
<th>low or unknown</th>
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</table>

Load Impedance

<table>
<thead>
<tr>
<th>high</th>
<th>high</th>
<th>high or unknown</th>
<th>low</th>
<th>low or unknown</th>
</tr>
</thead>
</table>

→ small C = higher SRF

Choose ferrite bead or inductors L which
= build no resonance with C
= broadband filter

Pay attention to:

SRF of used components
EMI NOISE SOURCES
Representative noise sources

- Input current caused by voltage ripple \( \rightarrow \) „Conducted Emission“
- Power traces and choke radiate EMI \( \rightarrow \) „Radiated Emission“
- Output current caused by voltage ripple \( \rightarrow \) „Conducted Emission“
- Radiated emission will increase by using long input / output lines(cables)
Conducted noise at converter input

- Conducted Emission is generated by voltage drop across $R_{\text{Sup}}$ and $\text{ESR}_{L}$
  \[ V_{\text{Noise}} = R_{\text{Sup}} \times I_{\text{in}} + \text{ESR} \times I_{\text{Cap}} \]
- $V_{\text{Noise}} = R_{\text{Sup}} \times I_{\text{in}} + \text{ESR} \times I_{\text{Cap}}$
- Resonance circuit is formed by $L_{\text{sup}}$, $C_{\text{in}}$ and $\text{ESL}_{C_{\text{in}}}$
  \[ f_0 = \frac{1}{2\pi \sqrt{(L_{\text{sup}}-\text{ESL}) \times C_{\text{in}}}} \]
- Different harmonics due to fundamental frequency from $f_{\text{DC/DC}}$ and $f_{\text{Resonance Circuit}}$
Conducted noise at converter output

- Conducted emission is generated by voltage drop at $ESR_C$
  \[ U_{Noise} = ESR_{Cout} \times I_{Cout} \]
- Resonance circuit is formed by $C_{D\text{converter}}$, $C_{Out}$, $L_{\text{Converter}}$, and $ESL_{Cout}$
  \[ f_0 = \frac{1}{2\pi \sqrt{(ESL_{Cout} \times C_{Out})}} \]
- Different harmonics due to fundamental frequency from $f_{DC/DC}$ and $f_{\text{Resonance Circuit}}$
Radiation of PCB traces

- Power and signal loops have antenna characteristics
- Radiation can occur over the entire power and signal loops
- Field strength depends on spanned loop, peak value of alternating current, frequency, distance between noise source and noise receiver

Design recommendations:
- Keep power and signal traces as short as possible
- Keep power and signal loops as small as possible
- Route the trace over GND plane

[Diagrams showing loop antenna, recommended, better, not recommended configurations]
FILTER DESIGN
„L“ Input filter (minimal recommend filter)

- Simple L-Filter
  - Input filter reduce current ripple on input line
  - Input filter reduce differential mode noise on input line
  - Input filter reduce radiated emission via input traces

Attention!!! This filter is not efficient to reduce common mode noise on input lines
Calculating input inductance

\[ L_{\text{filter}} = \frac{ESR(\text{DC})(1 - \text{DC})}{f\left(\frac{I_{\text{sup}}}{I_{\text{con}}} - \frac{ESR}{R_f}\right)} \]

- **ESR** = Effective series resistance of input capacitor
- **DC** = Converter duty cycle
- **I_{\text{con}}** = Peak-to-peak input ripple current
- **I_{\text{sup}}** = Required peak-to-peak ripple current for buck converters \( I_{\text{con}} \approx I_{\text{out}} \)
- **R_f** = “Damping” resistor (for lower Q)

For better filter performance choose next higher standard inductance value

**Example:**

\[ V_{\text{out}} = 5.0V \]
\[ I_{\text{out}} = 4.0A \]
\[ f = 2.5MHz \]
\[ ESR = 0.08\Omega \]
\[ DC = 0.5\% (50) \]
\[ I_{\text{con}} \approx I_{\text{out}} \]
\[ I_{\text{sup}} = 0.1A \]
\[ R_f = 0 \]

\[ L_{\text{filter}} = \frac{0.08\Omega \times 0.5(1 - 0.5)}{2.5MHz\left(\frac{0.1A}{4A} - 0\right)} = 320nH \]

➤ Choose 1μH (closest standard value)

- e.g.: WE-LQ “744 045 001”
- or: WE-PD2 “744 773 0”
Calculating rated current

- \( I_L = \frac{(V_{out})(I_{out})}{(V_{in})(E)} \)

\( V_{out} = \) Output voltage
\( I_{out} = \) Output current
\( V_{in} = \) Input voltage
\( E = \) Efficiency

For example:

- \( I_L = \frac{(5V)(4A)}{(20V)(0.8)} = 1.25A \)

- To avoid overload considerations choose a choke with higher rating current
- To avoid losses in efficiency choose a choke with low DCR
Wideband input filter
(recommended filter solution)

- T-filter recommend for wideband filtering
  - $L_{in}$ for low frequency filtering (DC/DC converter switching frequency)
  - Ferrite for high frequency filtering
  - $C_{filter}$ shorting ACnoise to GND ($220\text{pF} < C_{filter} < 1\text{nF}$, low ESR)

Attention!!! This filter is not efficient to reduce common mode noise on input lines
„L / C“ output filter
(minimal recommended filter)

- Simple L/C Filter
  - Output filter reduce voltage ripple on output traces (Conducted Emission)
  - Output filter reduce radiated emission via output traces (Radiated Emission)
  - No optimal solution for radio power devices

Attention!!! This filter is not efficient to reduce common mode noise on output lines
Calculating „L / C“ output inductor

\[ f_0 = \frac{1}{2\pi \sqrt{LC}} \quad \Leftrightarrow \quad L_{\text{filter}} = \frac{1}{(2\pi \frac{1}{10} f_0)^2 C_{\text{filter}}} \]

- Example:
  1. Choose capacitor e.g. 1µF, Electrolytic, low ESR
  2. Determine switching frequency of DC / DC converter
  3. Calculate inductor
  4. Choose next larger inductance value

\[ L_{\text{filter}} = \frac{1}{(2\pi \frac{1}{10} f_0)^2 C_{\text{filter}}} \quad \Leftrightarrow \quad L_{\text{filter}} = \frac{1}{(2\pi \frac{1}{10} 1.6MHz)^2 \times 1\mu F} = 989.5\text{nH} \]

\[ L = 1.0\mu\text{H} \]
„T“ - output filter
(recommended filter solution)

- T-filter recommend for wide bandwidth filtering
  - $L_{\text{filter}}$ for low frequency filtering (DC/DC converter switching frequency)
  - Ferrite for high frequency filtering
  - This kind of output filter is for powering radio devices high recommended

Attention!!! This filter is not efficient to reduce common mode noise on output line
Decoupling common mode noise

- For common mode rejection use common mode chokes
- For supplying over long distance common mode chokes are recommended
- Additional capacitor reduce differential mode noise
  - Small value for ceramic capacitor is recommended
  - Capacitor and common mode choke act as a LC - filter for differential mode noise
- Can be used for input and output lines
PCB - LAYOUT RECOMMENDATIONS
PCB-Layout recommendations

- Keep PCB traces as short as possible
- Avoid indirect trace routing
- Avoid any kind couplings → “capacitive”, “inductive”
- AC-current should flow across capacitor
- Short way for AC-current direct to GND (place double vias to GND)

T-filter

coupling path

not recommended

recommended
PCB-Layout recommendations

- Avoid indirect routing of power traces
- Avoid any kind of couplings \( \rightarrow \) “capacitive”, “inductive” … etc …
- AC-current should flow across common mode choke
- Route power traces on component layer
- Do not use vias
PCB-Layout recommendations

DC/DC buck converter

- Avoid GND planes under inductor (between inductor pads)
- Don’t route any kind of signals (analog, clock) under the inductor
- Fill out unused space on PCB with GND (flood)
PCB-Layout recommendations

Layer 1: power components
Layer 2: small signal
Layer 3: pure GND layer
Layer 4: small signal / controller components

- PCB-design of at least 4 layers is recommended
- Place a solid ground plane below the power component layer
- Minimize loops for power components
- Keep power traces as short as possible
- Establish good GND connections using low impedance vias

Recommended Diagram:
- Power components on top layer
- Pure GND layer on bottom layer
- Small signal / controller components in between

Not Recommended Diagram:
- Capacitive coupling between layers
- Mixed layer allocation
Magnetic field leakage

Shielded

Unshielded
Magnetic Field – Shielded vs. Unshielded

- Magnetic field

shielded vs. unshielded
Radiation by inductor

WE - PD2 unshielded
10\(\mu\)H, 2MHz Clock, 1A

WE – PD shielded
10\(\mu\)H, 2MHz Clock, 1A

19dBm difference
Magnetic leakage shielded vs. unshielded

unshielded

shileded

Channel: 2
Window Type: Blackman
Window Size: 8192

Cursor Information: Cursor off

Harmonic Information:
1st: 286.750 kHz -26.856 dB
3rd: 860.000 kHz -51.847 dB

2nd: 573.250 kHz -33.947 dB
4th: --

Channel: 2
Window Type: Blackman
Window Size: 8192

Cursor Information: Cursor off

Harmonic Information:
1st: 286.500 kHz -46.377 dB
3rd: 859.750 kHz -56.160 dB

2nd: 573.000 kHz -52.705 dB
4th: --
Magnetic Fields – Conducted Emission Measurement

Power supply V 1.0

Buck Converter ST L4960/2.5A/fs 85-115KHz
Magnetic Fields – Conducted Emission Measurement

Power supply V 1.1

PCB

Schematic
Magnetic Fields – Be Aware!

- Select the right parts for your application.
- Do not always look on cost.

Very easy solution with a dramatic result!

Choke before

or

Choke after
Boost converter Bad Example

Bad Example:
- Standard Alu-Electrolyte Cap Input/Output > ESR
- Power Inductor is not shielded
- Bad Layout with large Current Loops
- Power and Analog GND not separated
- No MOSFET Gate Resistor
- No Input&Output Filter
- Feedback Trace bad routing

A Boost Converter is critical at the Output!!
Boost converter Bad Example
Boost converter Bad Example no filter
Boost converter Bad Example with filter

Receiver

Input  DC  Att  10 dB  Preamp  OFF  Step LIN

<table>
<thead>
<tr>
<th>Level</th>
<th>dBµV</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Peak</td>
<td>30.24</td>
<td>100.000000 MHz</td>
</tr>
<tr>
<td>Average</td>
<td>18.31</td>
<td></td>
</tr>
</tbody>
</table>

Limit Check:
- Line 55022-AV: PASS
- Line 55022-QP: PASS

Start 150.0 kHz  Stop 100.0 MHz
Boost converter Good Example

Good Example:
- Low ESR Input Caps
- Low ESR Output Caps
- Input & Output Filter
- Low Impedance Layout
- Small Current Loops
- Fully shielded Power Inductor
- Signal GNDA is separated and quiet

Vin 5V/4.5A

Vout 12V / 2A

A Boost Converter is critical at the Output!!
Boost converter Good Example
Boost converter Good Example

Receiver

<table>
<thead>
<tr>
<th>Level</th>
<th>dBµV</th>
<th>Frequency</th>
<th>100.00000000 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Peak</td>
<td>25.81</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Average</td>
<td>21.71</td>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>

Scan

Limit Check:
- 1 MHz: PASS
- 10 MHz: PASS

Start 150.0 kHz
Stop 100.0 MHz
STORAGE INDUCTOR SELECTION
Inductor selection

Example: Step down converter

1. \( DC = \frac{U_{\text{out}}}{U_{\text{in}}} = \frac{5\text{V}}{15\text{V}} \approx 0,33 \)

2. \( I_{\text{rated}} \approx I_{\text{out}} = 1\text{A} \)

3. \( I_{\text{ripple}} \approx 20\%...40\% \cdot I_{\text{out}} = 0,2...0,4\text{A} \) (practical values)

4. \[
L = \frac{DC \cdot (U_{\text{in}} - U_{\text{out}})}{f_{\text{switch}} \cdot r \cdot I_{\text{out}}} = \frac{0,33 \cdot (15\text{V} - 5\text{V})}{200 \cdot 0,2 \cdot 1\text{A}}
\]

\[
L = 83....33\mu\text{H}
\]

\( \rightarrow \) choose average value 56\(\mu\text{H} \) to begin optimization
Inductor selection

Example: Step down converter

\[ I_{\text{out}} = 1A \quad \Rightarrow \quad I_{L_{\text{max}}} \approx 1.5A \quad \Rightarrow \quad I_{\text{sat}} \geq 1.5A \]

\[ L = 56\mu H \quad \text{at} \quad r = 0.3 \]

WE-PD Type 1260 744 771 156  \( I_{\text{rated}} = 2.01A \)  \( I_{\text{sat}} = 2.35A \)

RECOMMENDATION:
- test different inductor values
  → consider the tolerance of \( L \)-values
  → effect on the design (e.g. Ripple current; RDC)

choose additional:
744 771 133 + 744 771 168

\[ L = 33\mu H \quad L = 68\mu H \]
Inductor selection

Example: Step up converter

1. \[ DC = 1 - \frac{U_{\text{in}}}{U_{\text{out}}} = 1 - \frac{5V}{15V} \approx 0,667 \]

2. \[ I_{\text{rated}} \approx \frac{I_{\text{out}}}{1 - DC} = 3A \]

3. \[ I_{\text{ripple}} \approx 20\%...40\% \cdot I_{\text{out}} = 0,6...1,2A \] (practical values)

4. \[ L = \frac{(U_{\text{out}} - U_{\text{in}}) \cdot (1 - DC)^2}{f_{\text{switch}} \cdot r \cdot I_{\text{out}}} = \frac{(15V - 5V) \cdot (1 - 0,667)^2 \cdot s}{200E3 \cdot 0,2 \cdot 1A} \]

\[ L = 10....56\mu H \]

\( \rightarrow \) choose average value 33\( \mu H \) to begin optimization
**Inductor selection**

Example: Step up converter

\[ I_{\text{out}} = 1A \quad r = 0.5 \quad I_{L_{\text{max}}} \approx 3.75A \quad \rightarrow \quad I_{\text{sat}} \geq 3.5A \]

\[ L = 33\mu H \quad \text{at} \quad r = 0.2 \]

WE-PD Type 1280 744 770 133  \( I_{\text{rated}} = 3.20A \quad I_{\text{sat}} = 3.60A \)

**RECOMMENDATION:**
- test different inductor values
  - consider the tolerance of L-values
  - effect on the design (e.g. Ripple current; RDC)

choose additional:

744 770 9470 + 744 770 122

\[ L = 47\mu H \quad L = 22\mu H \]
Comparing different inductor values

- \( \Delta I_{peak} = 0.3A \)
- ripple range 20-50%

Inductor – ripple current

higher ripple current \( \rightarrow \) higher losses (AC)
Inductor - Rated current

- current load for power inductor can be calculated by
  → software

  → calculation step-by-step

  → use following approach as a simplified calculation

  \[
  I_{RMS_{inductor}} \approx I_{out\_application}
  \]

  \[
  I_{RMS_{inductor}} \approx \frac{U_{out}}{U_{in}} \cdot I_{out\_application}
  \]

  → BUCK

  → BOOST
Inductor – Saturation current

Buck -Regulator:
• \(I_{\text{peak}}\) Inductor

\[
I_{\text{Lmax}} = I_{\text{out}} \cdot \left(1 + \frac{I_{\text{rip}}}{2}\right)
\]

Boost-Regulator:
• \(I_{\text{peak}}\) Inductor

\[
I_{\text{Lmax}} = \frac{I_{\text{out}}}{1-DC} \cdot \left(1 + \frac{I_{\text{rip}}}{2}\right)
\]

Inductor should be not saturated
Definition of saturation currents

Würth Elektronik: e.g. WE-PD

- the saturation current always refers to a certain inductance drop and is individually...
What is saturation current?

![Inductance vs. Current (typ.)](image)

**What is saturation current?**

The graph represents the relationship between inductance (L) in microhenries (µH) and current (A) in amperes. The lines show the typical behavior of inductance as current increases, approaching saturation at higher current levels.
LIVE EMC DEMONSTRATION
AC/DC CONVERTER EMI
Transformers for EMC – What to choose?
Transformers for EMC – No external gaps

- Center leg gap only
  - Windings shield
- No gaps in outer legs
  - Nothing to shield

No Gaps here
Gap here
Transformers for EMC – No EI core

- EI core style
- Mylar or tape used for gap
- Three unshielded gaps

Not a good solution!
Transformers for EMC – Gap

- Gap must be perpendicular to flux lines
  - Here only one side is gapped
- Uneven gaps are inefficient. => Why?
  - Core saturates at minimum gap.
  - Requires a larger gap
- Also larger gap – More potential EMI
Transformers for EMC – Internal shields

- Shield both conducted and radiated noise
- Copper foil or wound magnet wire?
- Copper foil shields – Expensive, => Why?
  - Must build shield
  - Must be covered with tape
  - Winding machine stopped to apply
- All shields take away space from winding area
Transformers for EMC – External shields

- How do external shields differ from internal shields?
- Shield radiate noise only!
- As expensive as internal shields
Transformers for EMC – Y-Cap termination

- Noise couples through the transformer via $C_{ww}$
  - Noise seeks path to primary circuit
  - Without path, noise may become conducted emissions
- Y-Cap across transformer reduces noise
  - Tune the capacitor for optimum loss vs. noise reduction
  - Capacitor usually in the 470pF to 4.7nF range
  - Y-Caps to transformer terminals not on switch nor on diode
  - Close to transformer as possible

What Can We Do?
Decrease $C_{ww}$?

What Else Can We Do?
Transformers for EMC – Reducing $C_{ww}$

- High $C_{ww}$ causes conducted emissions
- May reduce $C_{ww}$, but what happens?
- Leakage inductance increases
- $L_{LKG}$ can be controlled by Snubber but efficiency and cost suffer
- Balance between $C_{ww}$ and $L_{leakg}$
Transformers for EMC – Power Supply
Transformers for EMC – Example 1

Pegel [dBμV]

- Without common mode choke
- With adjusted Snubber
- Without adjusted Y-Cap

QPeak
Avg.
Peak
Avg.

EMC- Test Failed

Freqenz [Hz]

150k 300k 500k 1M 2M 3M 5M 7M 10M 30M
Transformers for EMC – Example 2

- With common mode choke
- With adjusted Snubber
- Without adjusted Y-Cap

QEpeak
Avg.
Peak
Avg.

EMC- Test Failed

Pegel [dBμV]

100
80
60
40
20
0

150k 300k 500k 1M 2M 3M 5M 7M 10M 30M
Freqenz [Hz]
Transformers for EMC – Example 3

- With common mode choke
- With adjusted Snubber
- With adjusted Y-Cap

Pegel [dBµV]

<table>
<thead>
<tr>
<th>Pegel [dBµV]</th>
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<td>80</td>
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<td>40</td>
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Frequenz [Hz]

<table>
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<th>Frequenz [Hz]</th>
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</tr>
<tr>
<td>5M</td>
</tr>
<tr>
<td>7M</td>
</tr>
<tr>
<td>10M</td>
</tr>
<tr>
<td>30M</td>
</tr>
</tbody>
</table>

EMC- Passed

QPeak Avg.
Peak Avg.
Transformers for EMC – Example 4

- With common mode choke
- Without adjusted Snubber
- With adjusted Y-Cap

Pegel [dB\(\mu\)V]

<table>
<thead>
<tr>
<th>Frequenz [Hz]</th>
<th>QPeak Avg.</th>
<th>Peak Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>150k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7M</td>
<td></td>
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<tr>
<td>10M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EMC- Passed
Transformer for EMC – Conclusion for this power supply

- Necessary to pass EMI:
  - Common Mode Choke (CMC)
  - Y-Cap
- Not necessary to pass EMI
  - Optimized Snubber
Common Mode Noise Suppression
Radiated Emissions made by AC-DC Converter
No Filter- no Y -Cap

- Uin: 230Vac
- Iout: 1.5A
- Polarization: Horizontal
- Norm: EN55022A

![Graph showing radiated emissions](image)

- Uout: 24Vdc
- Fsw: 100kHz
- Polarization: Horizontal
- Norm: EN55022A
Radiated Emissions made by AC-DC Converter
No Filter- using Y -Cap

- Uin: 230Vac
- Iout: 1.5A
- Polarization: Horizontal
- Norm: EN55022A

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>30MHz</th>
<th>3GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>dBµV/m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/o Y-Cap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Y-Cap</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Radiated Emissions made by AC-DC Converter
Use Input Filter & Y-Cap
Radiated Emissions made by AC-DC Converter
With Input Filter & Y -Cap

- Uin: 230Vac  Uout: 24Vdc
- Iout: 1,5A  fsw: 100kHz
- Polarization: Horizontal
- Norm: EN55022A

dBµV/m

![Graph showing radiated emissions with and without input filter]
Conducted Emissions made by AC-DC Converter without Input Filter with Y-Cap

- $U_{\text{in}}$: 230VAC, $U_{\text{out}}$: 24VDC
- $I_{\text{out}}$: 1.5A, $f_{\text{sw}}$: 100kHz
- Measured: L to PE
- Norm: EN55022A

![Graph showing conducted emissions](image)
Conducted Emissions made by AC-DC Converter with Input Filter & Y-Cap

- $U_{\text{in}}$: 230VAC, $U_{\text{out}}$: 24VDC
- $I_{\text{out}}$: 1.5A, $f_{\text{CLK}}$: 100kHz
- Leitung: L nach PE
- Norm: EN55022A

**Graph:**
- Y-axis: dBµV
- X-axis: Frequency (MHz)
- Data points between 150kHz and 30MHz are plotted.
OTHER EMC SITUATION
FOR AC/DC CONVERTER
Radiated Emissions made by AC-DC Converter without Ferrite bead and without Y-Cap

- Uin: 230VAC
- Uout: 12VDC
- Iout: 4.16A
- fsw: 90kHz

![Graph showing radiated emissions with and without input filter](image)

**Graph Notes:**
- dBµV/m
- 30MHz to 1GHz
- Frequency (MHz)
- no Shielding
- With Input Filter

*Graph Description:*
- The graph compares radiated emissions with and without input filter.
- The y-axis represents the emission level in dBµV/m.
- The x-axis represents the frequency in MHz, ranging from 30MHz to 1GHz.
- The graph shows a significant reduction in emissions with the input filter.
Radiated Emissions made by AC-DC Converter with Ferrite bead and without Y-Cap

- Ferrite bead selection:
  - Check noise frequency
  - NiZn Ferrite bead
  - use WE-SAFB 4x2 mm, 250 Ohm @ 90 MHz

[Diagram with Ni-Zn Ferrite bead]
Radiated Emissions made by AC-DC Converter with Ferrite bead and without Y -Cap

- Uin: 230VAC, Uout: 12VDC
- Iout: 4,16A, fsw: 90kHz
- Polarization: Horizontal
- Norm: EN55022A

![Graph showing radiated emissions with and without ferrite bead](image-url)
Radiated Emissions made by AC-DC Converter with Ferrite bead and with Y-Cap

- **Selection of Y Cap**
  - High freq. type
  - High Voltage
  - Low ESR
  - Small package
  - Example: WCAP-CSSA 1nF

- **Selection of Ferrite bead:**
  - NiZn Ferrite bead
  - Small size bead
  - Example: WE-SAFB 4x2 mm, 250Ohm @ 90 MHz

Radiated Emissions made by AC-DC Converter with Ferrite bead and with Y-Cap
Radiated Emissions made by AC-DC Converter with Ferrite bead and with Y-Cap

- $U_{in}$: 230VAC, $U_{out}$: 12VDC
- $I_{out}$: 4.16A, $f_{sw}$: 90kHz
- Polarization: Horizontal
- Norm: EN55022A

![Graph showing radiated emissions](image-url)
Radiated Emissions made by AC-DC Converter with Ferrite bead and with Y-Caps + Snap Ferrite

- Uin: 230VAC, Uout: 12VDC
- Iout: 4.16A, fsw: 90kHz
- Polarization: Horizontal
- Norm: EN55022A

**Graph**

The graph shows the radiated emissions in dBµV/m across different frequencies with and without Snap Ferrite. The emissions with Snap Ferrite are significantly lower compared to those without it, especially in the frequency range of 30MHz to 1GHz.
Radiated Emissions made by AC-DC Converter with Ferrite bead and with Y–Caps + Shielding

- Uin: 230VAC, Uout: 12VDC
- Iout: 4.16A, fsw: 90kHz
- Polarization: Horizontal
- Norm: EN55022A

**Graph:**
- dBµV/m vs Frequency (MHz)
- Comparison between w/o Shielding and w/ Shielding
OTHER EMC SITUATION FOR A DC/DC CONVERTER
DC/DC Converter with galvanic separation
DC/DC Converter with galvanic separation
DC/DC Converter with galvanic separation 18V input no filter
DC/DC Converter with galvanic separation 24V input no filter
DC/DC Converter with galvanic separation 32V input no filter

Receiver

RBW (CISPR) 9 kHz MT 100 ms

Input DC Att 10 dB Preamp OFF Step LIN

Level dBμV Frequency
Max Peak 14.18 -20 0 20 40 60 80 100
Average 3.23 -20 0 20 40 60 80 100

Scan 1Pck Clrw 2Av Clrw

Limit Check
Line 55022-QP
Line 55022-AV

1 MHz FAIL
FAIL

Start 150.0 kHz Stop 30.0 MHz
DC/DC Converter with galvanic separation 24V input with input filter
MEASUREMENT TECHNIQUES
Conducted Emission test setup

- **LISN: „Line Impedance Stabilization Network“**
  - Create known impedance on power lines for DUT
  - Filter mains voltage and cut higher frequency
  - Transfer conducted emission noise to EMC-Receiver
- EMC-chamber is recommended but not required
DC-LISN

- DC-LISN allow measurement of conducted emission at DC/DC converters
- Decouple the DC from the EMC receiver
- Creates 50Ω impedance for EMC-receiver
- Just differential noise measureable
Ripple-Measurement

- for a clean external connection
OPTIMIZED TRANSFORMER
Schematic

Quelle: MPS EVHF01B00DB-00A
## Compare Transformers

<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>891 µH</td>
<td>907 µH</td>
<td>933 µH</td>
</tr>
<tr>
<td>Leakage Inductance</td>
<td>13,2 µH</td>
<td>20,7 µH</td>
<td>26,6 µH</td>
</tr>
<tr>
<td>Winding Capacity</td>
<td>53,1 pF</td>
<td>29,0 pF</td>
<td>64,9 pF</td>
</tr>
</tbody>
</table>
Transformer Construction

Type 1

N1 (2-4): 42Ts*2P*ø0,25mm
2 Layer

N2 (7-9): 14Ts*2P*ø0,5mm TIW
N3 (8-10): 14Ts*1P*ø0,5mm TIW
bifilar into 2 Layers

N3 (3-5): 8Ts*2P*ø0,25mm
Spread over 1 full Layer

N1 (1-2): 42Ts*2P*ø0,25mm
2 Layers

Type 2

N2 (7-9): 14Ts*2P*ø0,5mm TIW
N3 (8-10): 14Ts*1P*ø0,5mm TIW
bifilar into 2 Layers

N4 (3-5): 8Ts*2P*ø0,25mm
Spread over 1 full Layer

N1 (1-4): 84Ts*2P*ø0,25mm
2 Layers

Type 3

N2 (7-9): 14Ts*2P*ø0,5mm TIW
N3 (8-10): 14Ts*1P*ø0,5mm TIW
bifilar into 2 Layers

S1(NC-1): copper foil 15*0,05mm
packed in tape

N1 (1-4): 84Ts*2P*ø0,25mm
2 Layers

N4 (3-5): 8Ts*2P*ø0,25mm
Spread over 1 full Layer
Conducted Emissions with diff Transformers

Type 1:
Transformer with lowest Leakage Ind.

Type 2:
Transformer optimized Lowest Cost
Conducted Emissions with diff Transformers

Type 3:
Transformer with Shielding Winding

Transformer Type 3
With additional CMC and Ycap
EXAMPLES FOR BAD DESIGN
Example for Bad Design

- Schematic for AC/DC converter
- No Input Filter
- Bad Layout
Example for Bad Design

- High Emissions for Conducted
- QP & AV limits exceed
Example for Bad Design

- No Input Filter
- Simple Pi Filter → Layout mistake!
- Wrong positioned Filter
- Simple 2 Layer
- Bad routing
Example for Bad Design

- Un insolated DC/DC converter
- No input filter
- Bad Layout
Example for Bad Design

- High emissions for radiated
- Limits over shoted
Example for Bad Design

- No input filter
- Simple 2 layer
- Wrong position for output capacity
- Bad Ground routing
Simulation – WEBENCH

- [http://www.we-online.de/web/de/electronic_components/toolbox_pbs/webench.php](http://www.we-online.de/web/de/electronic_components/toolbox_pbs/webench.php)
Simulation – LTSpice IV

- http://www.linear.com/designtools/software/#LTSpice

This example schematic is supplied for informational/educational purposes only.
Energy Harvesting to Go kit

- Environment energy captured and converted into electricity for small autonomous devices making them self-sufficient.

- Thermo Electric Generator (heat)
- Piezo Electric (vibration/strain)
- Photovoltaic (light)
- Galvanic (chemical)
- Induction (motion)

Energy Management & Storage

Regulated Voltage
WE WPCC Demo Kit
Wireless Power Coils WE-WPCC- Tx/Rx coils

- Fully compliant to WPC Qi standard
- Efficiency up to 85%
- Supreme shielding characteristics for low leakage inductance
- Outstanding performance due to usage of Litz wire:
  - lowest $R_{DC}$
  - highest Q values
MagI³C Power Module
DC/DC Step Down Converter with integrated inductor

- Branch:
  - Industrial
  - Communication
  - Audio/Video equipment
  - Test & Measurement equipment
  - Medical

- Application area:
  - Voltage supply
  - Multi-Voltage Systems
  - Software developers with no hardware knowledge

5 types with variable output voltage
2 types with variable output voltage
MagI³C Power Module
DC/DC Step Down Converter with integrated inductor

Power Module Concept

Controller IC

I_{SWITCH 1}

V_{IN}

I_{LOAD}

V_{OUT}

I_{SWITCH 2}

Lead frame
MagIIIc Step-Down Regulator Power Module Family

Output Range:
- 5-24V
- 0.8-6V
- 2.5-15V
- 0.8-3.6V
- 3.3V / 5.0V @0.5A

V<sub>IN</sub> [V]

QFN

TO263

SIP

I<sub>OUT</sub> [A]
Trilogy of Magnetics

- 1. LTspice Book
  → How to use and build spice models
- 2. Trilogy of Magnetics
  → Design Guide for EMI Filter Design, SMPS & RF Circuits
- 3. Trilogy of Connectors
  → Basic Principles and Connector Design Explanations
- 4. ABC of Power Modules
  → Functionality, Structure and Handling of a Power Module
- 5. ABC of Capacitors
  → Basic principles, characteristics and capacitor types
!!! Questions ???

- Do you *still think* ...

  ... that a DC/DC converter *“does not generate Conducted Emission”* ???

  ... that the EMC of a DC/DC converter *“isn’t affected by the PCB layout”* ???

  ... that an *“oscilloscope can’t help you to carry out any EMC tests”* ???
If you still have questions?

Just call us: we try to help you

Don’t give up !!!
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- Distribution
- Factories
Würth Elektronik eiSos GmbH & Co.KG

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