Topic 2

Understanding Noise-Spreading Techniques and their Effects in Switch-Mode Power Applications

John Rice, Dirk Gehrke, and Mike Segal
Agenda

1. Quantifying the SMPS noise problem
   - Problem Definition
   - Measurement Techniques and EMC Standards
2. Clarifying the principles of SSFD*
   - Implementing Modulation
   - Using simulation to predict harmonic peak reduction
3. Application of SSFD*
   - Conducted: Power Factor Correction
   - Radiated: Automotive
4. Conclusion

*SSFD = Spread-Spectrum Frequency Dithering
A Definition of Electromagnetic Compatibility: (EMC)

"You can watch football with your TV set-top box sitting on a working PC"

- **Conducted Emissions**
  - Differential (Normal) Mode
  - Common Mode

- **Radiated Emissions**
  - Electric Field ~ Voltage
  - Magnetic Field ~ Current

SEM1500, Topic 1: Understanding & Optimizing EMC in SMPS
Disturbances Generated by SMPS

**Electromagnetic Emission:**

- **Sources of H-Field radiation**
  - Winding leakage fields
  - Primary loop area
  - Secondary loop area

- **Source of E-Field radiation**
  - High dv/dt on conductive surfaces
  - High frequency on ripple cables
Graphical Prediction of Harmonic Spectrum

- Trapezoidal Waveform

\[
T = \text{the period of the repetitive waveform}
\]
\[
\tau = \text{pulse width at the 50\% points}
\]
\[
A = \text{pulse amplitude}
\]
\[
t_r = t_f = \text{pulse rise and fall times}
\]

Simulated Response \(\rightarrow\)
1 MHz, 50\% duty cycle
\[
\tau = 480 \text{ ns} \quad \text{and} \quad t_r = t_f = 20 \text{ ns}
\]

- Fourier Envelope, Nomogram

\[
20 \log (2A \tau / T) = f_1 = 1 / \pi \tau
\]
\[
20 \log (2At_r / T) = f_2 = 1 / \pi t_r
\]

Amplitude (dB)

Log Frequency (Hz)

Amplitude (V)

Frequency (Hz)
Limits and Units of EMI Power Measurement

Converting dBm to dBµV

\[
\text{dB} = 10 \log_{10} \left( \frac{P}{P_{\text{ref}}} \right) = 20 \log_{10} \left( \frac{V}{V_{\text{ref}}} \right)
\]

\[P = \frac{V^2}{R}, \quad R = 50 \ \Omega \text{ impedance} \]

\[
dB(P) = 10 \log_{10} \left( \frac{V^2}{R} \right) = 20 \log_{10}(V) - 10 \log_{10} R
\]

\[\rightarrow \log(a^n) = n \log a \]

\[\rightarrow \log(a/b) = \log a - \log b \]

\[\text{dBW (ref = 1 W)} = 10 \log_{10} P \]

\[\text{dBm (ref = 1 mW)} = \text{dBW} + 30 \]

\[\text{dBV} = 20 \log_{10} V \]

\[\text{dBµV (ref = 1 µV)} = \text{dBV} + 120 \]

\[\text{dBmW} - 30 = (\text{dBµV} - 120) - 10 \log_{10} 50 \]

\[\therefore \text{dBµV} = \text{dBm} + 107 \]

CISPR 22 and FCC Part 15 Conducted Emission Limits
The Swept Spectrum Analyzer (SA)

◆ Basic SA block diagram

◆ Display response
  (Relative to IF filter RBW)

Narrowband – Signal contained within the receiver bandwidth

Broadband – Signal not fully contained within the receiver IF bandwidth
Understanding Detector Operation (simplification)

- **Peak Detector**
- **Quasi-Peak Detector**
- **Average Detector**

Diagram showing the operation of peak detection, quasi-peak detection, and average detection for short and long repetition periods.
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*SSFD = Spread-Spectrum Frequency Dithering
First Conceptualization of “Spread Spectrum” (SSFD)

Eva Maria Kiesler aka “Hedy Lamarr”
Explaining Harmonic Spreading with FM Theory

- Sine modulation of a square wave

\[
\text{Period } (t) = \frac{1}{f_c \left[ 1 + \left( \Delta f \times \sin 2\pi f_m t \right) / f_c \right]}
\]

Spread-spectrum parameters:
- Modulation frequency, \( f_m \)
- Center frequency, \( f_c \)
- Frequency deviation, \( \Delta f \)
- Other modulation shapes triangular, exponential, complex

\[ \beta = \Delta f / f_m = \text{modulation index} \]
Periodic Modulation Waveforms
and their Spreading Effect

Parameters:
- $f_m = 10$ kHz
- $\Delta f = 31$ kHz
- $t_p = t_f = 10$ ns
- $V_o = 310$ kHz

Energy of $f_0$ spread into band:
$$BT = 2(\Delta f_c + f_m) = 2(\beta+1)f_m$$

Energy of $f_n$ spread into band:
$$BT_n = 2f_m(1+n\beta)$$

Fundamental reduction between unmodulated (black) waveform and triangular (green) waveform = 7 dB
**TPS40200EVM-001 Simulation Model**

\[ i_n = \frac{V_{in}}{68.1 \, k} = 104 \, \mu A \]

\[ i_m = \frac{V_m}{56 \, k} = 17.8 \, \mu A \]

\[ f_{max} = \frac{f_c(i_n + i_m)}{i_n} \]

\[ f_{min} = \frac{f_c(i_n - i_m)}{i_n} \]

\[ \delta = \frac{\Delta f}{2f_c} = \frac{100 \, k}{2 \times 295 \, k} = 0.17 \]

**Rate of Modulation** (center spreading):

**Modulation Index:**

\[ \beta = \frac{\Delta f}{f_{min}} = \frac{100 \, k}{13 \, k} = 7.7 \]
Conducted Emission Testing: Line Impedance Stabilization Network (LISN)

Purpose:
1. Present a constant impedance to the DUT power cord
2. Block external conducted emissions from adding to the measurement
3. Transfer high-frequency conducted emissions to the measurement equipment

![Diagram of LISN Circuit]
Predicted Waveforms in Steady-State

- Output Ripple $V_{out}$ (V)
- LISN Output (V)
- OSC Ramp (V)
- Switch Node (V)
- Error Amplifier Output (V)
Predicted Spectral Response of Line Current

- Simulated LISN output at 50% duty cycle
- Modulation: $f_m = 13$ kHz triangular wave
- Predicted fundamental reduction = 13 dB (higher than measured due to input-filter parasitics and resonance)
Measured Spectral Content of Line Current

- LISN output at 50% duty cycle
- FFT RBW = 222 Hz
- Modulation = 13-kHz triangular wave
- Actual fundamental reduction = 7.7 dB
Complex-Wave Modulation: Pseudo-Random

- Linear-feedback shift register (LFSR) made up of 17 flip flops and XOR gate create a \((2^{17} - 1)\) repeating pseudo-random sequence

- XOR acts as linear feedback to achieve maximum-length sequence according to the feedback polynomial

<table>
<thead>
<tr>
<th>Bits</th>
<th>Feedback polynomial</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>(x^4 + x^3 + 1)</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>(x^5 + x^3 + 1)</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>(x^6 + x^5 + 1)</td>
<td>63</td>
</tr>
<tr>
<td>7</td>
<td>(x^7 + x^6 + 1)</td>
<td>127</td>
</tr>
<tr>
<td>8</td>
<td>(x^8 + x^6 + x^5 + x^4 + 1)</td>
<td>255</td>
</tr>
<tr>
<td>9</td>
<td>(x^9 + x^5 + 1)</td>
<td>511</td>
</tr>
<tr>
<td>10</td>
<td>(x^{10} + x^7 + 1)</td>
<td>1023</td>
</tr>
<tr>
<td>11</td>
<td>(x^{11} + x^9 + 1)</td>
<td>2047</td>
</tr>
<tr>
<td>12</td>
<td>(x^{12} + x^{11} + x^{10} + x^4 + 1)</td>
<td>4095</td>
</tr>
<tr>
<td>13</td>
<td>(x^{13} + x^{12} + x^{11} + x^8 + 1)</td>
<td>8191</td>
</tr>
<tr>
<td>14</td>
<td>(x^{14} + x^{13} + x^{12} + x^2 + 1)</td>
<td>16383</td>
</tr>
<tr>
<td>15</td>
<td>(x^{15} + x^{14} + 1)</td>
<td>32767</td>
</tr>
<tr>
<td>16</td>
<td>(x^{16} + x^{14} + x^{13} + x^{11} + 1)</td>
<td>65535</td>
</tr>
<tr>
<td>17</td>
<td>(x^{17} + x^{14} + 1)</td>
<td>131071</td>
</tr>
</tbody>
</table>
Pseudo-Random Modulation

- Uniform spreading, maximum reduction of fundamental
- Predicted attenuation of $f_0 > 30$ dB
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Why Power-Factor Correction (PFC)?

- Reduce harmonics of $I_{AC}$
- Minimize Phase Angle between $V_{AC}$, $I_{AC}$

![Diagram of AC Line Load and C Hold-Up](image-url)
2-Phase Interleaved Boost Converter

- Attenuates input ripple current
- Reduces capacitor RMS current

(See SEM1700 Topic 5)
UCC28070 Interleaved PFC with SSFD

Set $\Delta f$, $f_m$
UCC28070: Setting Dither Magnitude and Rate

- Modulation Waveshape: Triangular

- Dither Magnitude  \((\Delta f = 30 \text{ kHz})\)
  
  \[ R_{\text{RDM}} = \frac{937.5}{f_{\text{DM}}(\text{kHz})} = 31.6 \text{ k}\Omega \]

- Dither Rate  \((f_m = 10 \text{ kHz})\)
  
  \[ C_{\text{CDR}} = 66.7 \times \left[ \frac{R_{\text{RDM}}(\text{k}\Omega)}{f_{\text{DR}}(\text{kHz})} \right] = 220 \text{ pF} \]
Peak Conducted EMI: 150 kHz to 30 MHz

- SSFD reduces peaks at both low and high frequencies

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Amplitude (dBµV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.15</td>
<td>30</td>
</tr>
<tr>
<td>130</td>
<td>110</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
</tr>
</tbody>
</table>

Without Dither = 113 dBµV at 340 kHz

With Dither = 109 dBµV at 330 kHz

Resolution BW = 9 kHz

Input = 120 VAC, Load = 640 W, Input Filter: Corcom 15EJT1

LISN: Solar 9509-50-R-24-BNC, SA: HP8591EM
Quasi-Peak Conducted EMI at ~330 kHz

Resolution BW = 9 kHz

Without Dither = 113 dBµV at 339 kHz

With Dither = 108 dBµV at 328 kHz
Average Conducted EMI at ~330 kHz

Resolution BW = 9 kHz

Without Dither = 109 dBµV at 338 kHz
With Dither = 104 dBµV at 328 kHz
PFC Summary (Interleaved, 120 VAC, 640 W)

- With and Without Dither (30-kHz magnitude, 10-kHz rate)
  - ~330 kHz: >4-dB decrease (Peak, $Q_{pk}$ and AVG)
  - 20~30 MHz: >5-dB decrease

![Graph showing frequency and amplitude comparison between with and without dither.]

- Without Dither = 113 dBµV at 340 kHz
- With Dither = 109 dBµV at 330 kHz
- Resolution BW = 9 kHz
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TPIC74100 Buck-Boost Converter

- Modulation waveshape: Triangular
  ∆f = ±110 kHz, 330 ~ 550 kHz

- Integrates power FETs
  Input: 1.5 to 40 VDC
  Output: 5 V @ 1 A

- F_s = 440 kHz (nom)
  Adjustable:
  - Dither Rate
  - Slew Rate of Q1
TPIC74100 EVM2 Schematic

- 12-V $V_{\text{batt}}$
- 5-V $V_{\text{OUT}}$ 625 mA

- $F_s = 440$ kHz (nom)
- Input = 12-V Battery, Output = 5 V at 625 mA
- No input-filter inductor (JP1 shunts L2)
- CISPR25 Setup, 1-m monopole (NB) antenna
Peak—No Dither (0.15 ~ 30-MHz Band)

- Slowing slew rate reduces 20 ~ 30-MHz peaks
Peak—28-kHz Dither Rate
(0.15 ~ 30-MHz Band)

- Highlighted peaks were 42 and 26 without dither

- 35 dBµV/m (7 dB less)
- 20 dBµV/m (6 dB less)
Peak—56-kHz Dither Rate
(0.15 ~ 30-MHz Band)

- Highlighted peaks were 35 and 20 with 28-kHz dither
Peak—No Dither (30 ~ 200-MHz Band)

- Slower Slew reduces peaks, especially above 108 MHz

NOTE: In FM band (76-108 MHz) noise floor increase due to wider RBW, not switcher.
Peak—Slowest Slew (30 ~ 200-MHz Band)

- 56-kHz dither reduces peaks, especially below 60 MHz

NOTE: In FM band (76-108 MHz) noise floor increase due to wider RBW, **not** switcher.
Automotive DC/DC Summary

- Tested TPIC74100 EVM2 Radiated Emissions (RE)
  - Without input filter choke
  - PCB layout NOT optimized for EMC

- Slew Rate Control
  - Little impact on RE from 150 kHz to 30 MHz
  - Reduces RE from 30 MHz to 200 MHz

- Dither reduces RE at both low and high frequencies

- As dithering rate increases, peaks are reduced
Additional Considerations of SSFD

- Tends to raise the noise floor
- Potential audible noise (if $f_m$ in audible range)
- May increase ripple
- Magnetics – design for $\Delta f$
Conclusions

Spread-Spectrum Frequency Dithering (SSFD):

- **CAN facilitate EMC:**
  - Total-noise energy is unchanged
  - However,
  - Narrowband becomes broadband
  - Spectral peaks are reduced
  - May reduce input filter size and cost

- **Is NOT a substitute for careful attention to:**
  - Layout
  - Component selection
  - Shielding
  - etc…