

Consideration of Snubber Capacitors for Fast Switching with an Optimized DC Link



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Overview

- Introduction
- Equivalent circuit
- Impedance curves
- Case studies
- Practical example
- Discussion



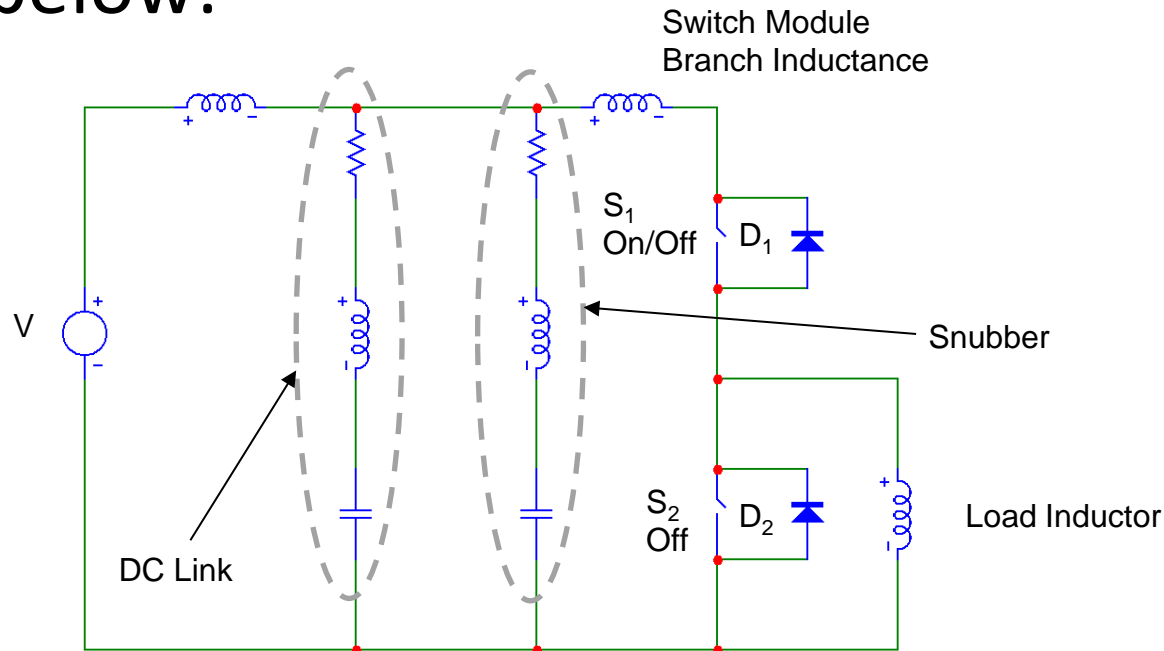
Introduction

- The use of snubber (e.g. bypass or de-tuning) capacitors can help to reduce voltage overshoot due to stray inductance
- How is the efficacy of snubber capacitors impacted by the following:
 - DC link inductance
 - Switch inductance
 - Switching speed
- Consider from impedance viewpoint...

Equivalent Circuit



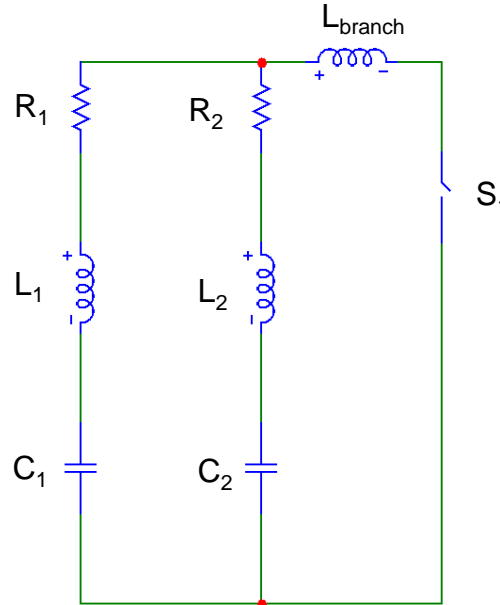
- Half-bridge switch modules are often tested using the “double pulse” method with the circuit below:



Equivalent Circuit (cont)



- At switch S_1 turn-off, D_2 conducts and the impedance network seen by the switch S_1 can be simplified as shown:



An Evolving Topology Landscape



- We will first look at an ideal (unrealistic) case to explain what the snubber is doing
- Then we will include a more realistic scenario with real world components
- The next step is an optimized DC link
- Finally we will increase switching frequency and show the results of optimized components and packaging

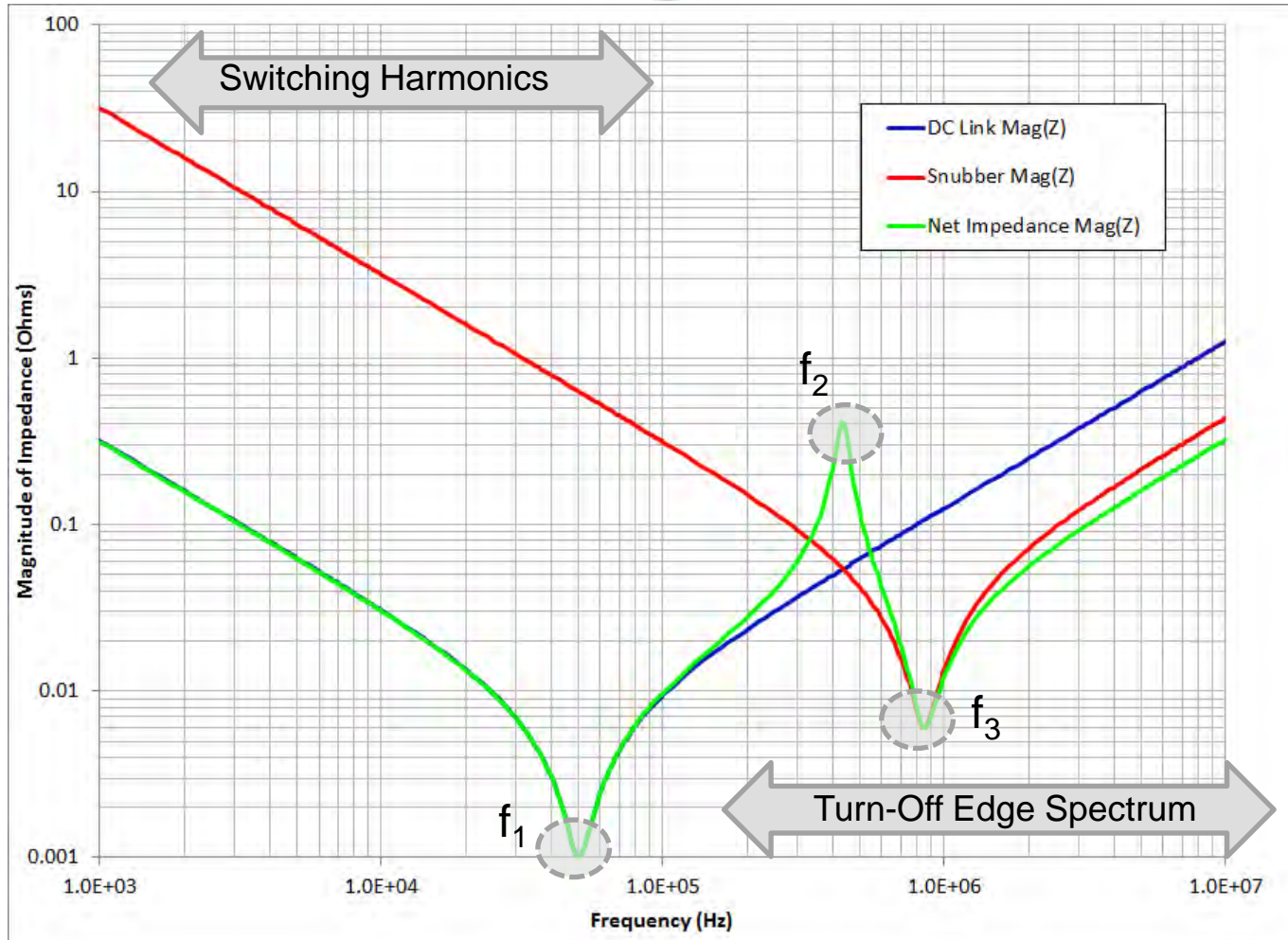


Impedance Curves



- Consider what happens to the energy stored in the stray inductances...
- Base case
 - $L_{\text{branch}} = 0$ (look at module terminals)
 - DC Link: $R_1 = 1\text{m}\Omega$, $L_1 = 20\text{nH}$, $C_1 = 500\mu\text{F}$
 - Snubber: $R_2 = 6\text{m}\Omega$, $L_2 = 7\text{nH}$, $C_2 = 5\mu\text{F}$
- Look at impedance spectrum...

Impedance Curves (cont)



Impedance Curves

Why should we care?



- We have three important frequencies
 - f_1 is the resonant frequency of the DC link defined by L_1 and C_1
 - f_2 is the resonant frequency of the DC link branch and the snubber branch defined by $L_1 + L_2$ and C_2 (for purpose of this discussion focus on f_1 and f_3)
 - f_3 is the resonant frequency of the snubber branch defined by L_2 and C_2
- Below 50kHz, the capacitance of the DC link dominates
 - Switching harmonics
- Inductance of snubber dominates above 500kHz
 - Broad spectrum of fast turn-off “edge”

Impedance Curves

Why should we care?



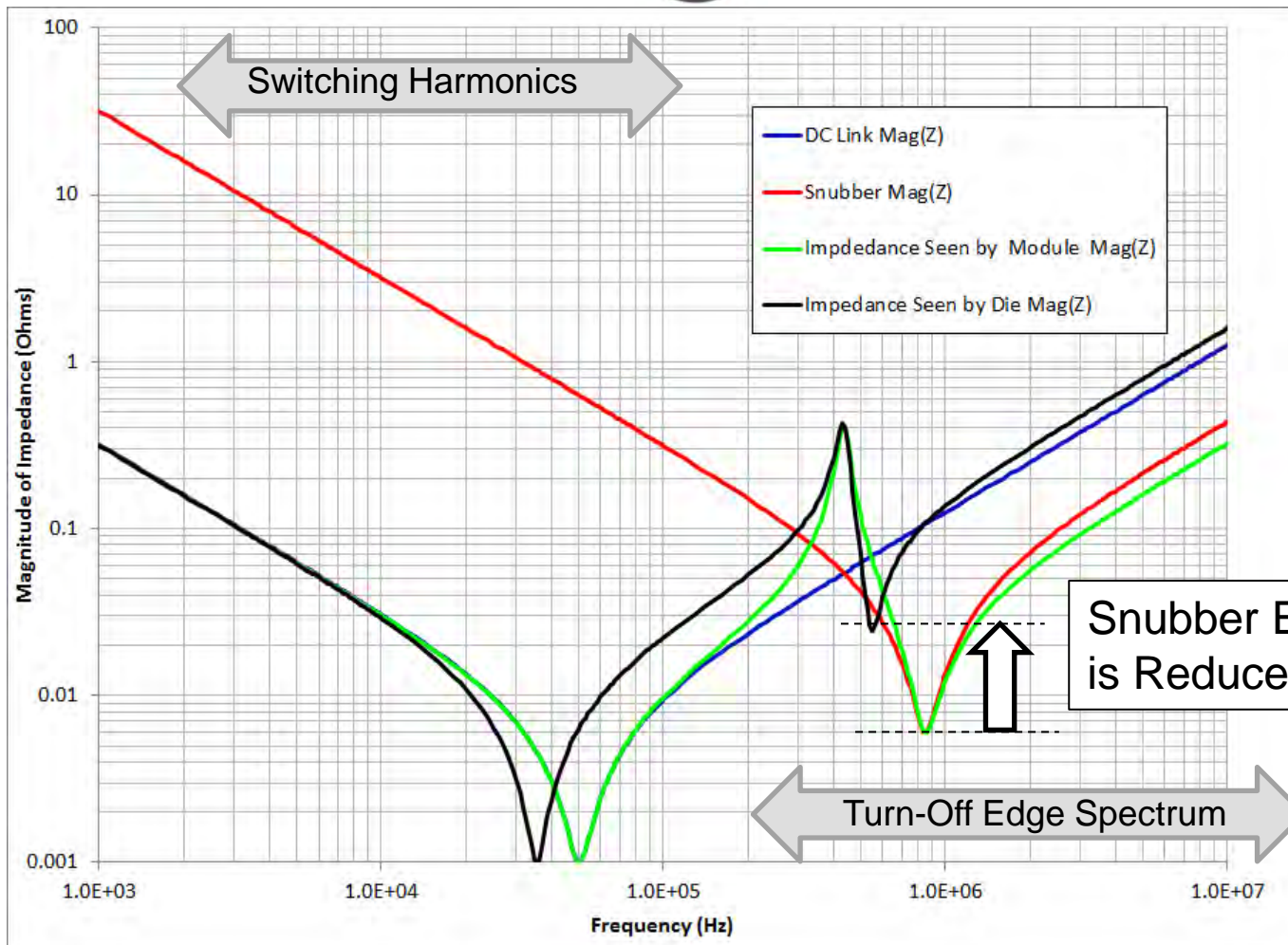
- When the net impedance is LOW at a resonant frequency, the LOW impedance device easily accepts energy
 - This is good for its neighbor (e.g. the switch) but bad for the device as it usually gets hot from the energy it accepts and dissipates

Case Study – Typical Installation



- The effectiveness of the snubber is reduced as L_{branch} becomes significant and typical components are used
 - $L_{\text{branch}} = 20\text{nH}$ (look at the die)
 - DC Link: $R_1 = 1\text{m}\Omega$, $L_1 = 20\text{nH}$, $C_1 = 500\mu\text{F}$
 - Snubber: $R_2 = 6\text{m}\Omega$, $L_2 = 7\text{nH}$, $C_2 = 5\mu\text{F}$
- The minimum impedance across the die is much higher than the previous case therefore snubber effect on the switch is reduced

Case Study – Typical Installation

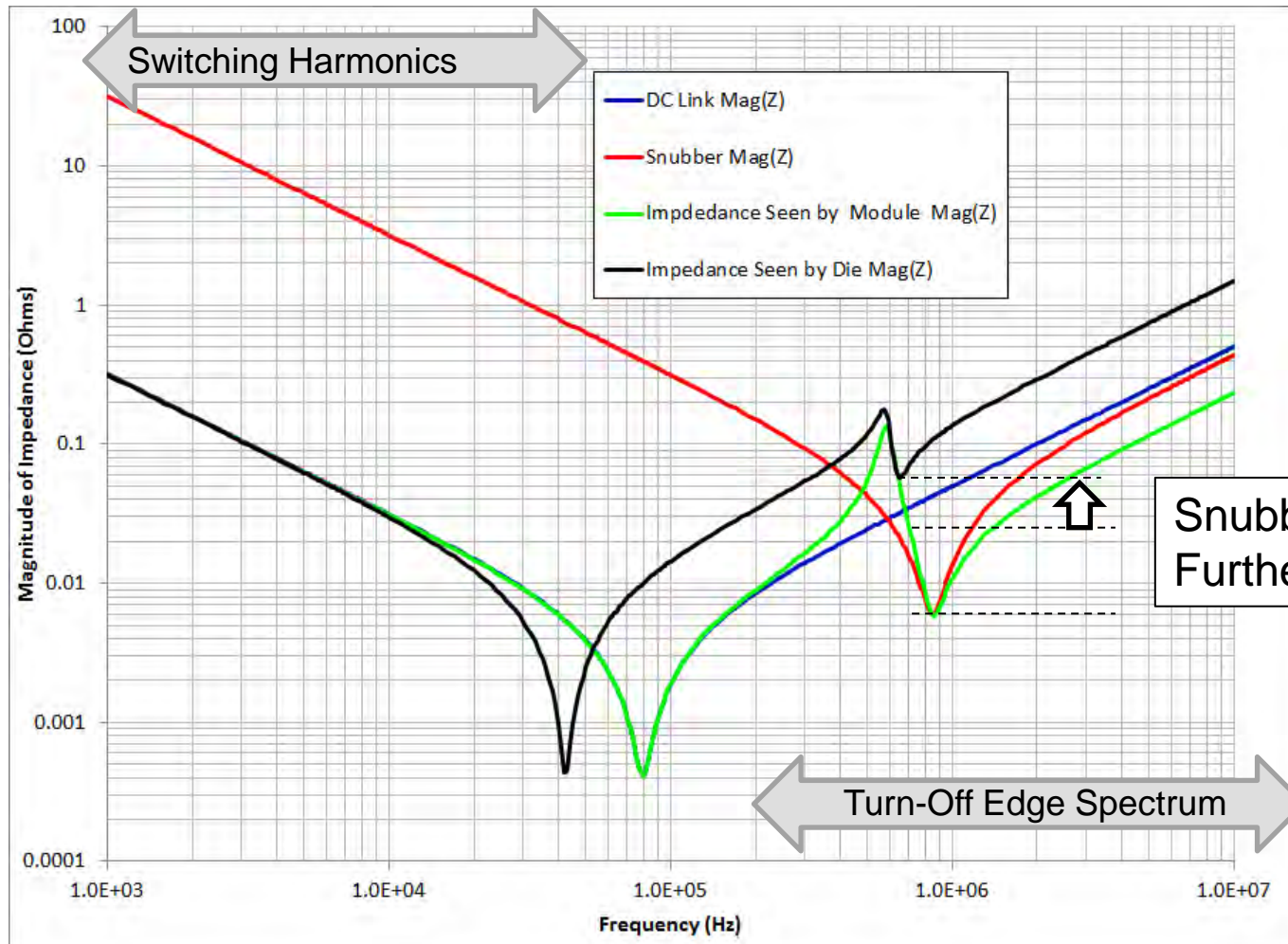


Case Studies – Optimized DC Link



- Now consider a high performance DC link system
- With an integrated cap/bus, a much lower inductance is possible
 - $L_{\text{branch}} = 20\text{nH}$
 - DC Link: $R_1 = 0.410\text{m}\Omega$, $L_1 = 8\text{nH}$, $C_1 = 500\mu\text{F}$
 - Snubber: $R_2 = 6\text{m}\Omega$, $L_2 = 7\text{nH}$, $C_2 = 5\mu\text{F}$
- Effect of snubber is further reduced

Case Study – Optimized DC Link





Practical Example



- Consider a typical EV traction drive using a “six pack” IGBT module with conventional silicon
 - 8 - 16kHz switching frequency
 - Snubber capacitors installed directly on IGBT input terminal pairs
 - Conventional DC link with discrete capacitors

Practical Example (cont)



- Every time a switch turns off
 - Energy is handed off to snubber branch via resonance f_3
 - This energy is dissipated in the snubber capacitor and DC link via resonance f_2
 - The snubber's ESR dominates
- Each snubber cap thus experiences an RMS current and average power loss that leads to temperature rise
 - The “average power” increases with the switching frequency
 - A 40kHz switching frequency has 5x more average power than 8kHz

Practical Example (cont)



- The snubber is a small thermal mass, usually with poor access to cooling
 - Terminals are directly coupled to IGBT inputs which are heated by:
 - IGBT die and bond wire losses
 - Bus losses
- The net result is that the snubber's safe operating temperature for desired life can be easily exceeded (a reliability problem) – and it gets worse with increasing switching frequency...

Practical Example (cont)



- Now consider what happens for the same scenario using silicon carbide devices
 - Much faster switching is possible to achieve greater efficiency
- Assume a 40kHz switching frequency
 - The snubber duty cycle is now increased by a factor of 5x from the silicon inverter
 - The power losses and temperature rise in the snubbers will increase by 5x

Practical Example (cont)



- Note that silicon carbide can operate at a higher junction temperature, so the device input terminals can also run hotter
- The increased switching frequency provides higher average power since the snubber accepts energy more often (directly related to frequency)
- Net result is that conventional snubber caps can easily exceed safe operating temperature in silicon carbide applications – limiting life and rated power

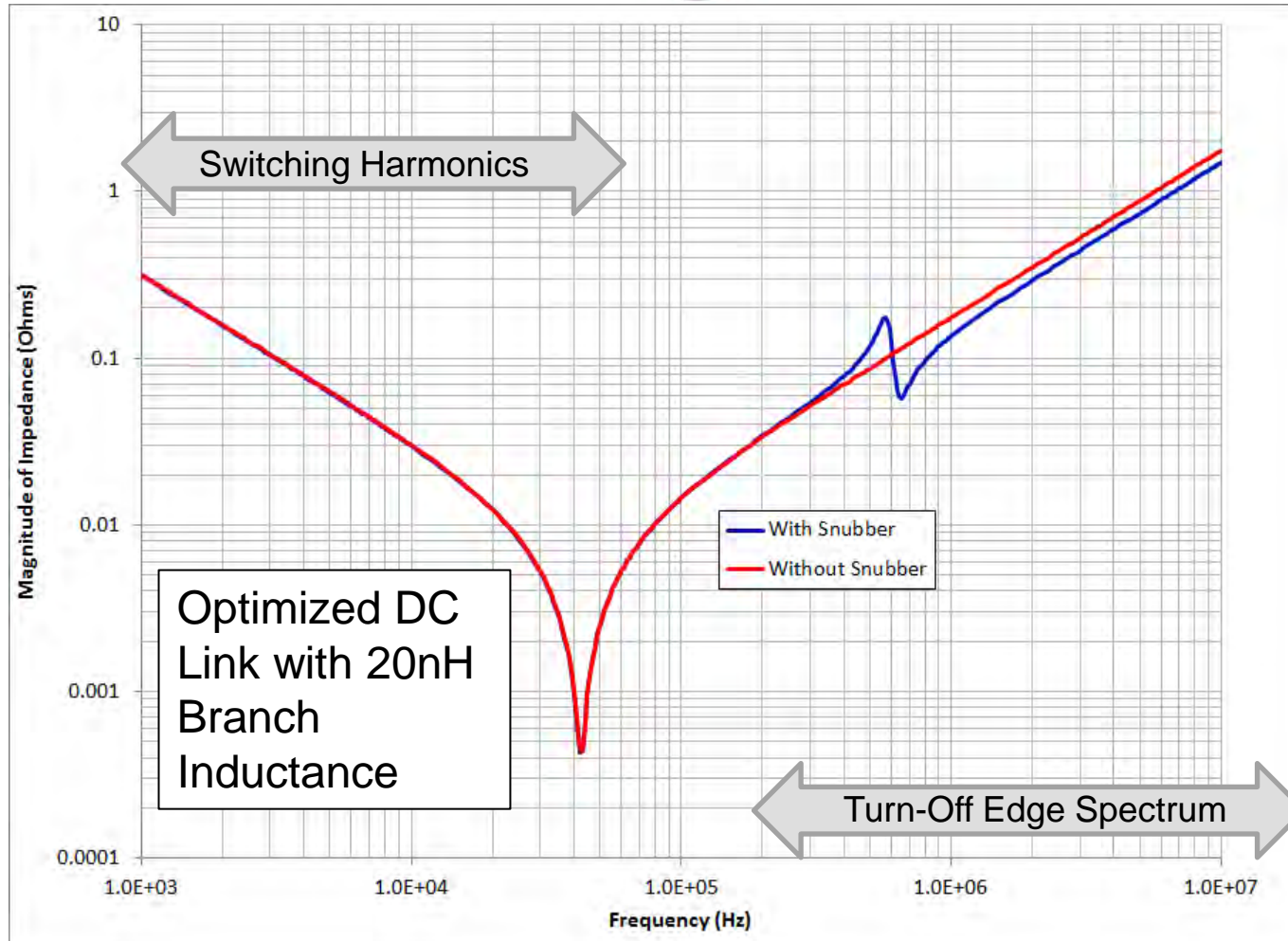


Optimized Example



- Going back to the high performance DC link case study, a better approach exists...
 - Tightly couple the DC link capacitor to the device inputs using an integrated capacitor/bus
 - Inductance on the same order as (or less than) the snubber capacitor
 - Merge the snubber and DC link into a single device
 - Use the SBE Power Ring Film Capacitor™ with very low ESR and ESL

Optimized Example





Optimized Example



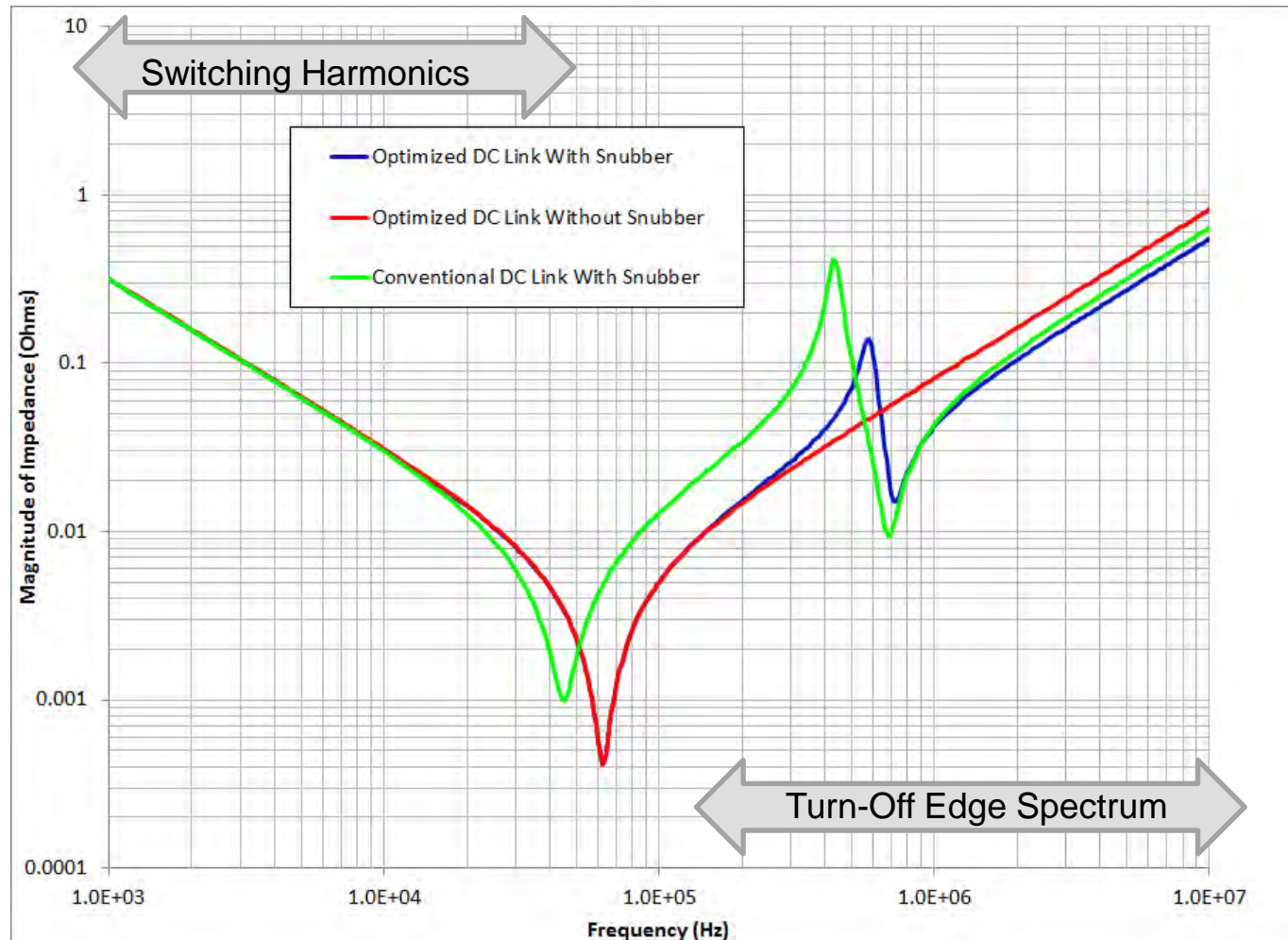
- The integrated DC link cap/bus can be readily interfaced with system cooling
 - Vertical stack approach
 - Lower losses and low thermal resistance translates into minimal temperature rise = no reliability issue
- Low effective ESL minimizes voltage overshoot
- Solve overshoot problem without introducing a weak link to the system design – even at high frequencies

Optimized Switch Packaging



- Up to this point, we have considered relatively high branch inductances using “typical” switch module packaging
- Leaders in the industry are working on optimized module designs...
- What happens with these next generation packages where branch ESL is at 3 - 5nH?

Optimized Switch Packaging (cont)



Optimized Switch Packaging (cont)



- The stored energy that the snubber will have to dissipate is less due to reduced conducting branch inductance, but higher switching frequency still provides a net increase of average power
 - Consider 20nH branch + 8nH DC Link
 - Going to 5nH branch reduces ESL from 28nH to 13nH and energy stored by a factor of 2.15
 - Going from 8kHz to 40kHz switching increases average power by 5x
 - **Increase in snubber power dissipation is still 2.3x**

Optimized Switch Packaging (cont)



- Conventional DC link and snubber offer no improvement in performance compared SBE integrated cap/bus



Discussion



- Snubbers cannot compensate for branch inductance inside the switch module
- High performance DC link with integrated cap/bus offers ESL on the same order (or lower) than snubber cap and virtually the same overshoot reduction with no penalty in system power rating, lifetime, or reliability



Discussion (cont)



- High performance DC link cap/bus ultimately becomes a snubber capacitor that also sources ripple current
- Switch packaging is becoming the limit of high frequency switching systems
 - Module companies are beginning to change this
- Whatever direction the modules take, the snubber will remain the weak link