Design Consideration in Selecting the Switching Frequency of Power Controllers

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Agenda

- Introduction
- Case Study
- Concepts and analysis
  - Minimum On Time
    - Minimum duty cycle capability
    - Effects of pulse skipping
  - Size
    - Filter selections
    - Filter comparisons
  - Efficiency
    - Power loss and thermal roadblocks
    - Efficiency comparisons
  - Performance
    - Bode Plots
    - Transient response
    - Ripple
- Competition
- TI Power Management devices > 1MHz
- Summary

Industry Trends

- Board space is becoming more valuable as density requirements increase
- Performance DSP and FPGA core voltage are dropping <1V
- Suppliers are aggressively marketing faster DC/DC Converters that claim to save space
  - How much space is really saved?
  - What are the trade offs and pitfalls?

Three Designs Compared

Design Example:

- Input Voltage: 5V
- Output voltage: 1.8V
- Output Current: 3A
- Output voltage Ripple: 20mV
- Inductor Ripple Current: 1A peak to peak

Switching Frequencies

- 350kHz
- 700kHz
- 1.6MHz

TPS54317 Selected

- Supports up to 1.6MHz
- Marketed as small sized design for high-density DSP & FPGA applications

TPS54317

1.6MHz, 3-6Vin, 3-A Step Down Converter

Features

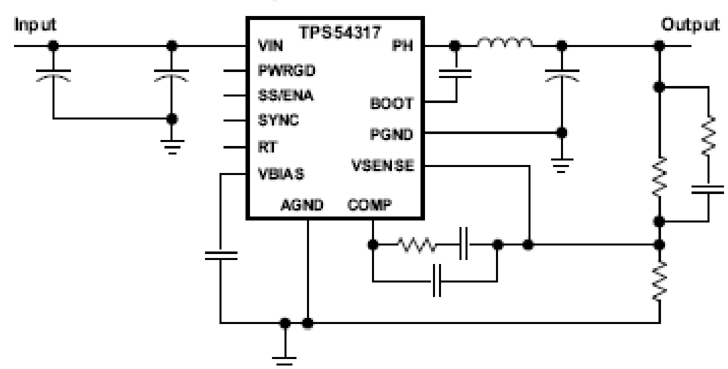
- Adjustable / synchronized switching frequency to 1.6MHz
- Supported by free SWIFT™ Software tool
- Two integrated MOSFETs provide synchronous rectification
- Output voltage adjustable down to 0.9V
- Power Good, Enable, Adj. Slow-start, Current Limit, Thermal Shutdown, & 1% accuracy
- 4x5mm 24pin thermal QFN package

Benefits

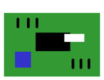
- High frequency allows a smaller inductor and capacitor to save board space
- Fast and easy design in minutes
- High efficiency greater than 90%; regulates at no load
- Ideal for DSP/FPGA power
- Many integrated protection and performance features to protect the system when powering advanced processors
- High current density saves board space

Applications

- 3.3/5V Intermediate Bus for high density point of load power systems
- Broadband, networking, and optical communications
- Point of Load Regulation for DSPs, FPGAs, & ASICs



EVM



TPS54317EVM-159

$2.50 @1K

Inductor Selection

Know V = L * di/dt

$L = V * \Delta I / \Delta t$

$L \geq V_{out} * (1-D)/(\Delta I \times F_s)$; with ΔI = 1A peak to peak

- 350kHz $L \geq 3.3\ \mu H$ → Choose $3.5\ \mu H$
- 700kHz $L \geq 1.7\ \mu H$ → Choose $2.2\ \mu H$
- 1.6MHz $L \geq 0.7\ \mu H$ → Choose $1.0\ \mu H$

Capacitor Selection

Know: **$R = V/I$** → ESR ≤ ΔV/ ΔI; use 0 mΩ for ceramic

$I = C * dv/dt$ → $C \geq \Delta I /(8 * Fs * \Delta V)$

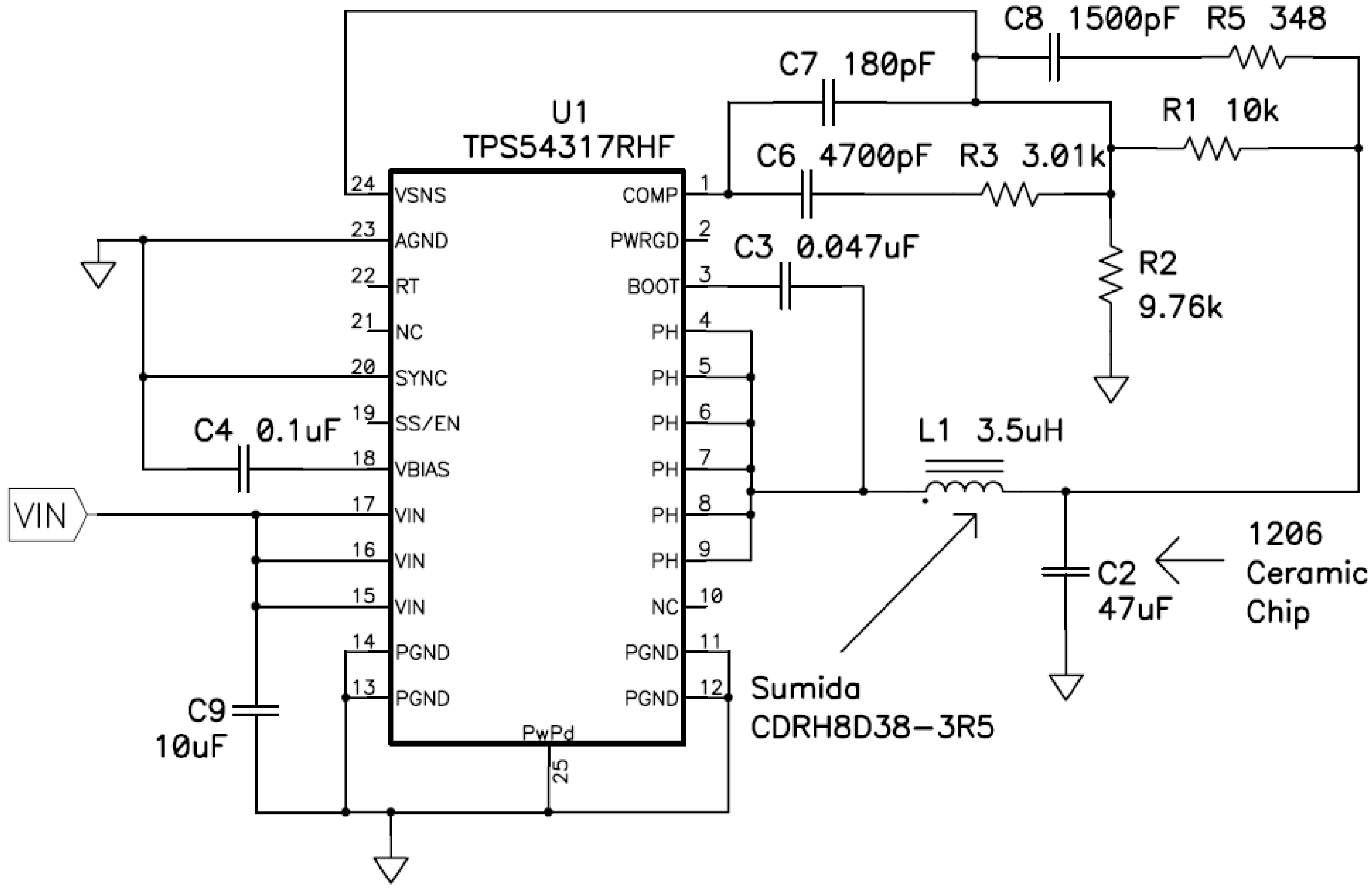
Total $\Delta V = \Delta I / (8 * C * Fs) * 2$ (to account for DC bias)

Design #1: 350kHz
- $C \geq 36\ \mu F$ → Choose 47μF 1206 ceramic

Design #2: 700kHz
- $C \geq 18\ \mu F$ → Choose 22μF 0805 ceramic

Design #3: 1.6MHz
- $C \geq 7.9\ \mu F$ → Choose 10μF 0603 ceramic

Design Example #1



<u>350kHz</u>

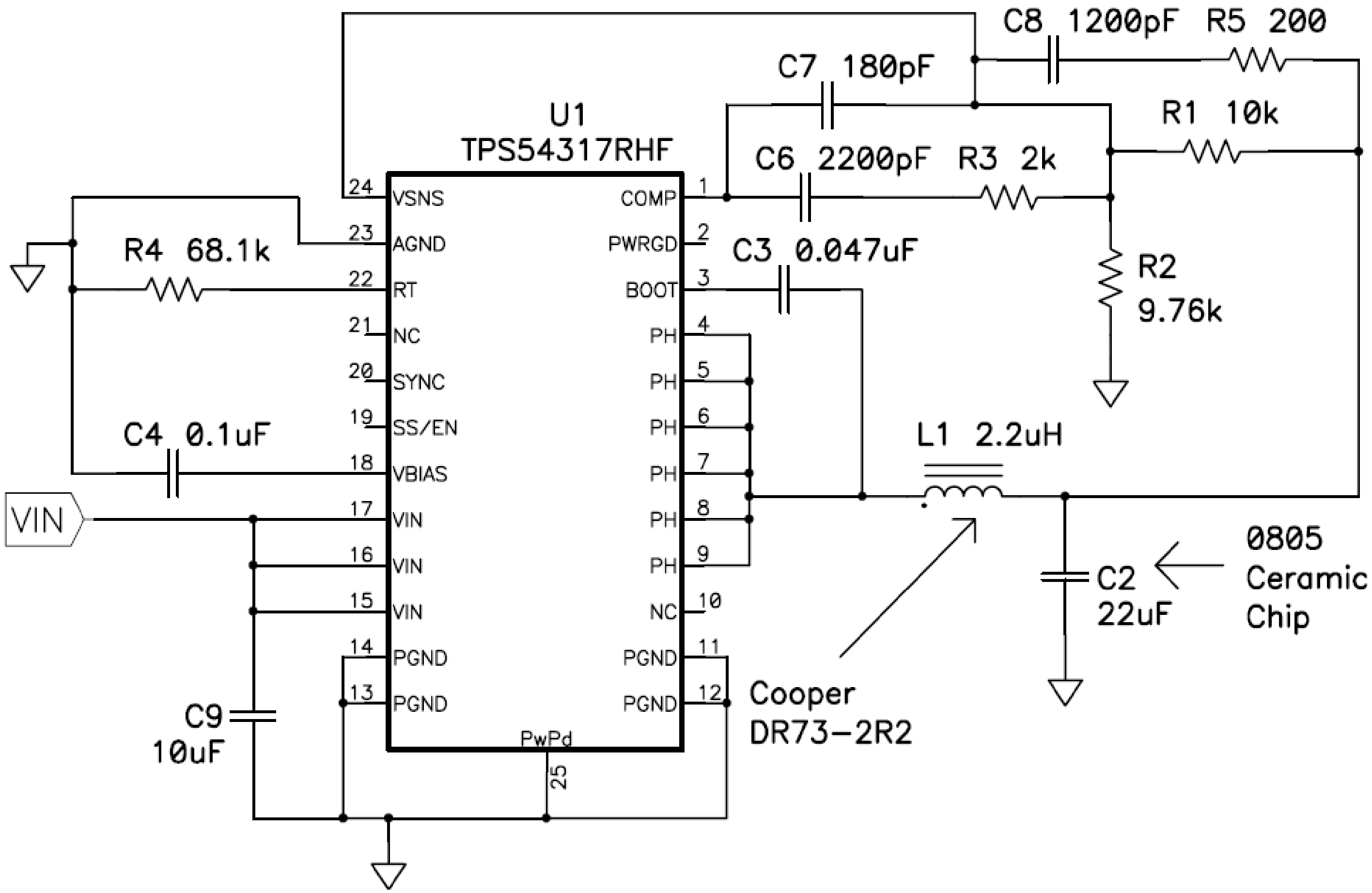
Inductor:

- Sumida
- 3.5µH
- 19 mΩ

Capacitor:

- 47µF
- 1206

Design Example #2



<u>700kHz</u>

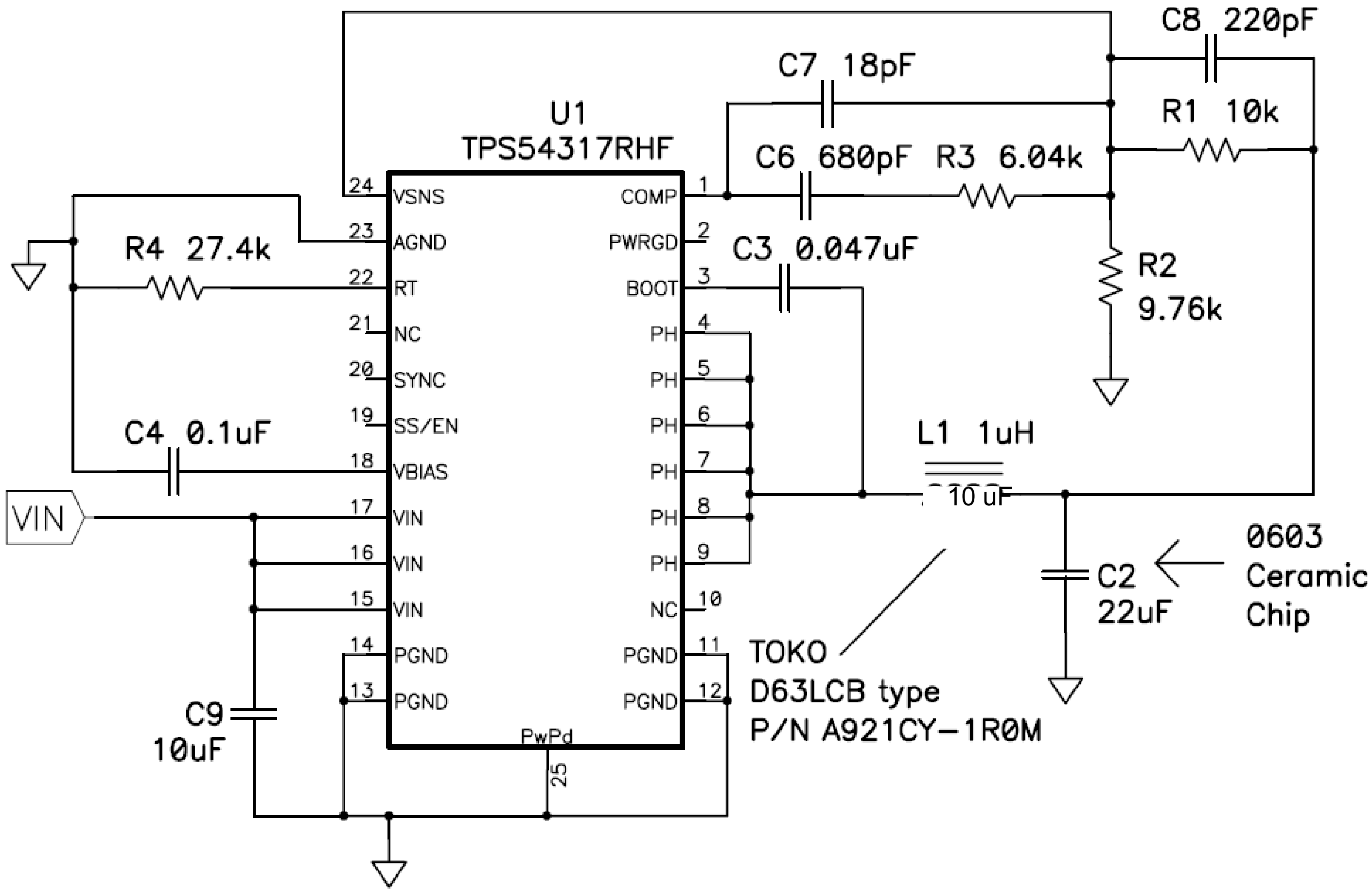
Inductor:

- Cooper
- 2.2µH
- 16.5 mΩ

Capacitor:

- 22µF
- 0805

Design Example #3



<u>1.6MHz</u>

Inductor:

- Toko
- 1μH
- 11 mΩ

Capacitor:

- 10μF
- 0603

Minimum *Controllable* On-Time

DC/DC Converters won't always work over a wide Vout/Vin Range.

– Check the minimum controllable on time in the datasheet, not the maximum oscillator frequency.

TPS54317 datasheet

		Min	typ	max	
Frequency range, SYNC		330		1600	kHz
Ramp valley[(1)]			0.75		V
Ramp amplitude (peak-to-peak)[(1)]			1		V
Minimum controllable on time				150	ns
Maximum duty cycle		90%			

– Check if the Vout/Vin (duty cycle) combination will work when the switching frequency and the minimum controllable on time are known.

Min. Duty Cycle = Min. On time * Switching Frequency

For 5Vin, 1.8Vout, 150ns min. on-time examples:

Frequency	Min. Duty Cycle	Minimum Vout
350 kHz	0.0525	→ OK - below Vout minimum of IC
700 kHz	0.12	→ OK - below Vout minimum of IC
1.6 MHz	0.24	→ OK 1.2V
3MHz	*0.45*	*→ 2.3V (pulse skipping*)

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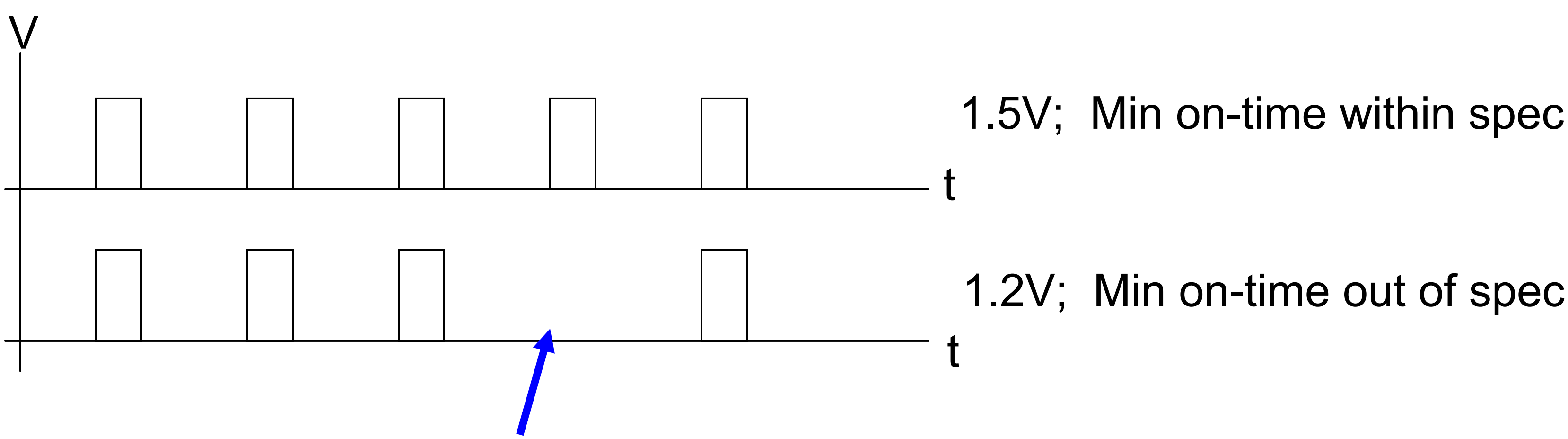
Minimum On-Time Issues

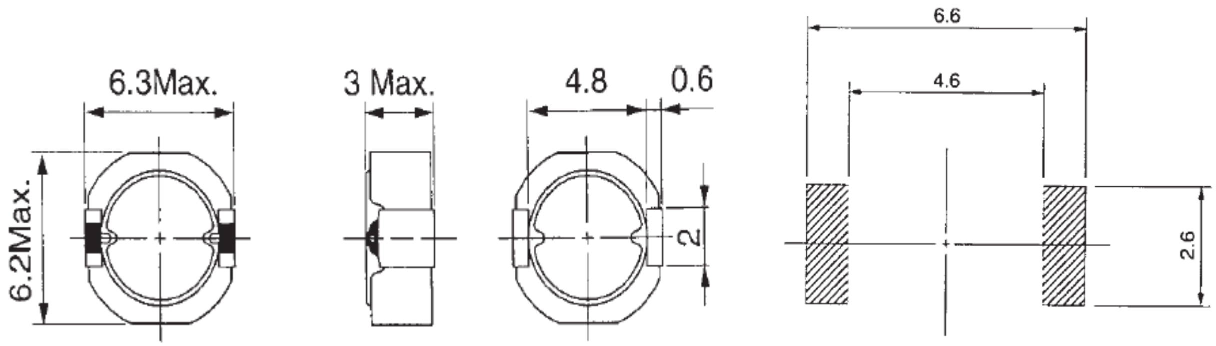
Pulse skipping happens when the DC/DC converter cannot extinguish the gate drive pulses fast enough to maintain the desired duty cycle. The power supply will still regulate the output voltage, but…

- Ripple voltage increases due to the pulses being further apart
- Frequency is no longer fixed
- Current limit may no longer work since the IC cannot respond in time
- Control loop may be unstable. Transient response is also affected

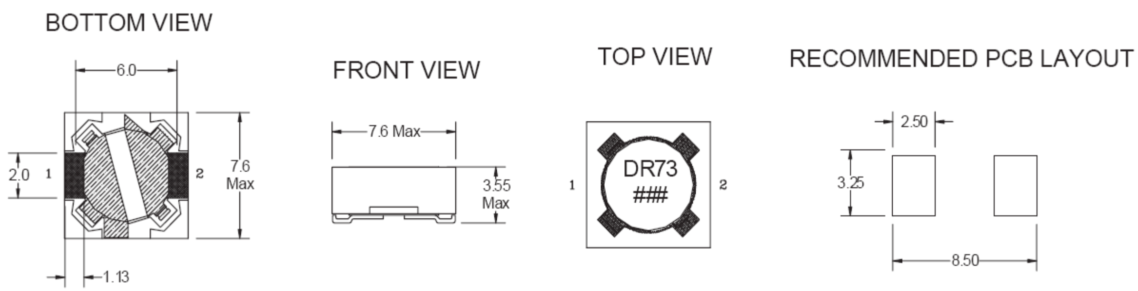


Controller misses a pulse to maintain desired regulation. Drop the Vin.

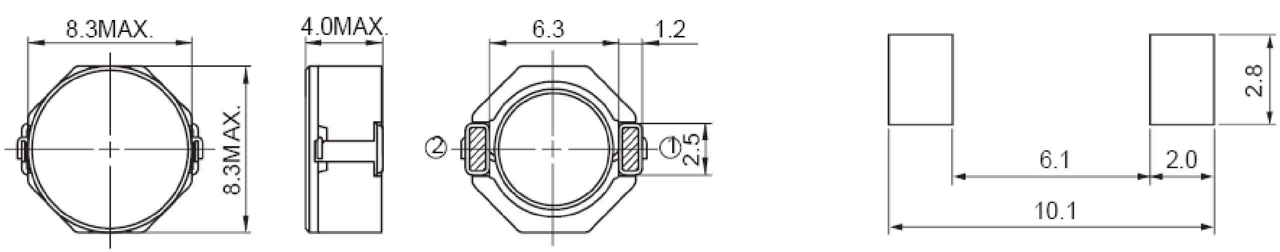
Inductor Size Comparison



TOKO
1.6MHz
1.0µH
11mΩ



COOPER
700kHz
2.2µH
16.5mΩ



SUMIDA
350kHz
3.5µH
19mΩ

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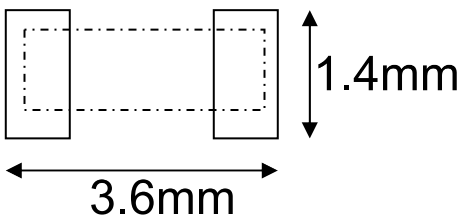
Capacitor Size Comparison

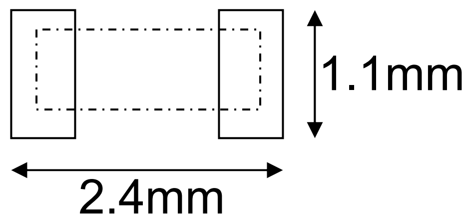
350 kHz Design

47µF



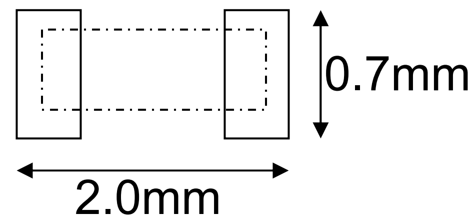
700 kHz Design

22µF



1.6 MHz Design

10µF



Frequency	Capacitor Land-pad size	Inductor Size	Filter Area (w/o spacing)	Total area (with spacing)
350kHz	5mm^2	84mm^2	89mm^2	260mm^2
700kHz	2.6mm^2	65mm^2	67.6mm^2	216mm^2
1.6MHz	1.4mm^2	41mm^2	42.4mm^2	163mm^2

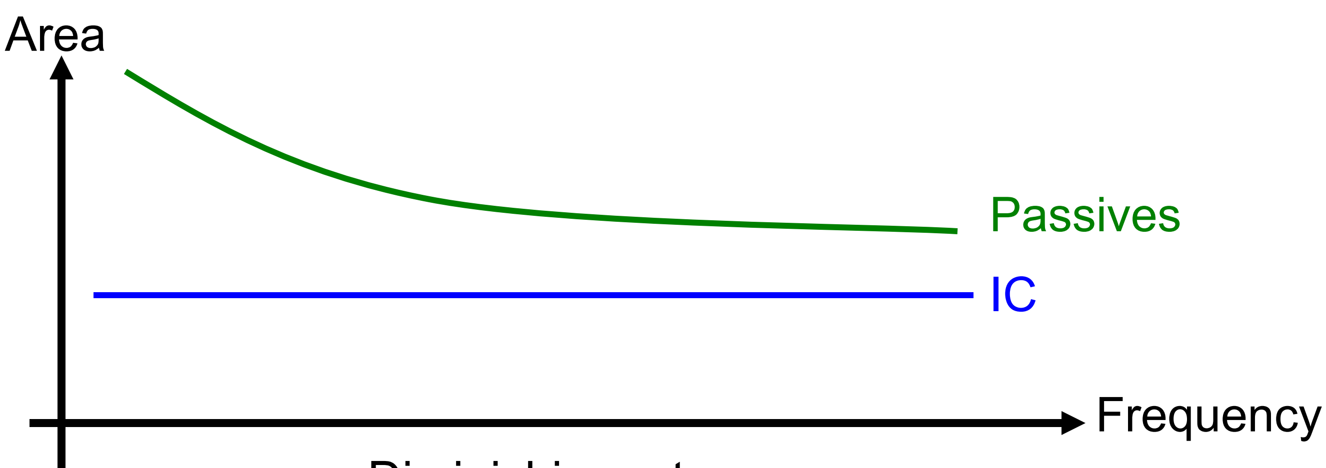
Filter Size Comparison

Consider Capacitor Package:

- Capacitors are available in fixed sizes
- ESR must be maintained as the case size is reduced

Consider Inductor Volume:

- Taller inductors may take up less board area, but pose a height issue
- Inductor Volume = $L * i^2 / 5x10^{-3}$



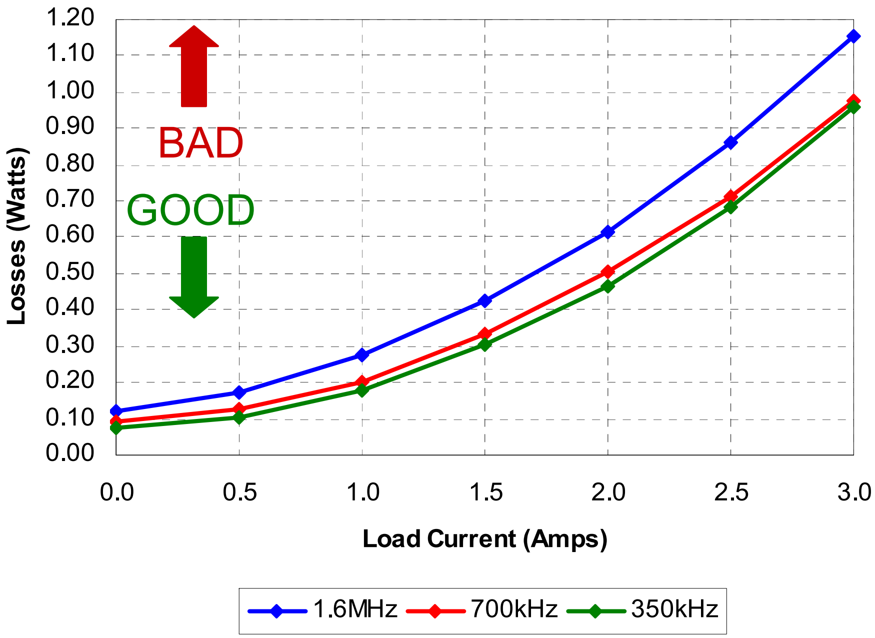
Diminishing returns

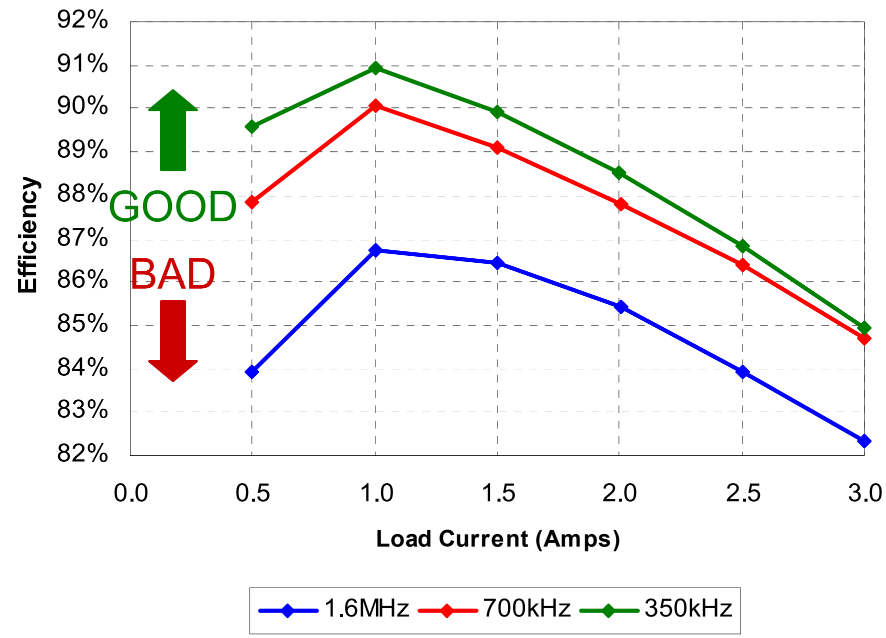
Efficiency

Power dissipation comes from several places including:

- FET driving loss (Qg * V * F):
  - FET drive loss is proportional to the switching frequency
- FET switching loss function of Vin, Iout, Ton/off, F
  - Switching loss is proportional to the switching frequency
- FET resistance (I^2 * Rds(on))
  - Same FET – little variance in these examples
- Inductor loss (I^2 * DCR + Core losses):
  - DCR losses may be reduced when Inductance is smaller
  - AC losses are proportional to the frequency
- Capacitor loss (I_{RMS}^2 * ESR):
  - Capacitor loss is negligible
- IC loss (Iq):
  - Same IC – no variance in these design examples

Efficiency Results

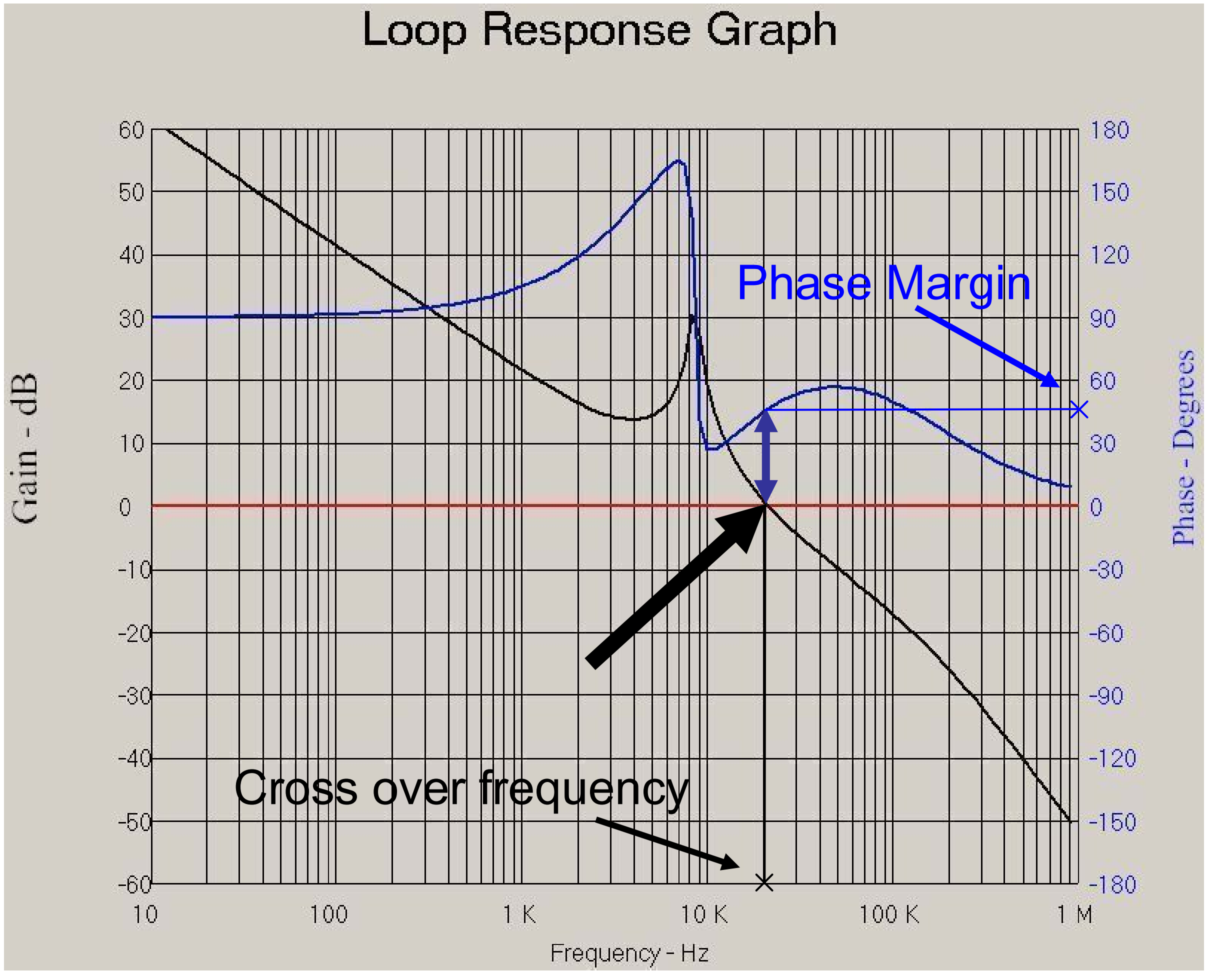




Dissipated power turns into heat:

Frequency	IC temperature
350kHz	45° C
700kHz	48° C
1.6MHz	52° C

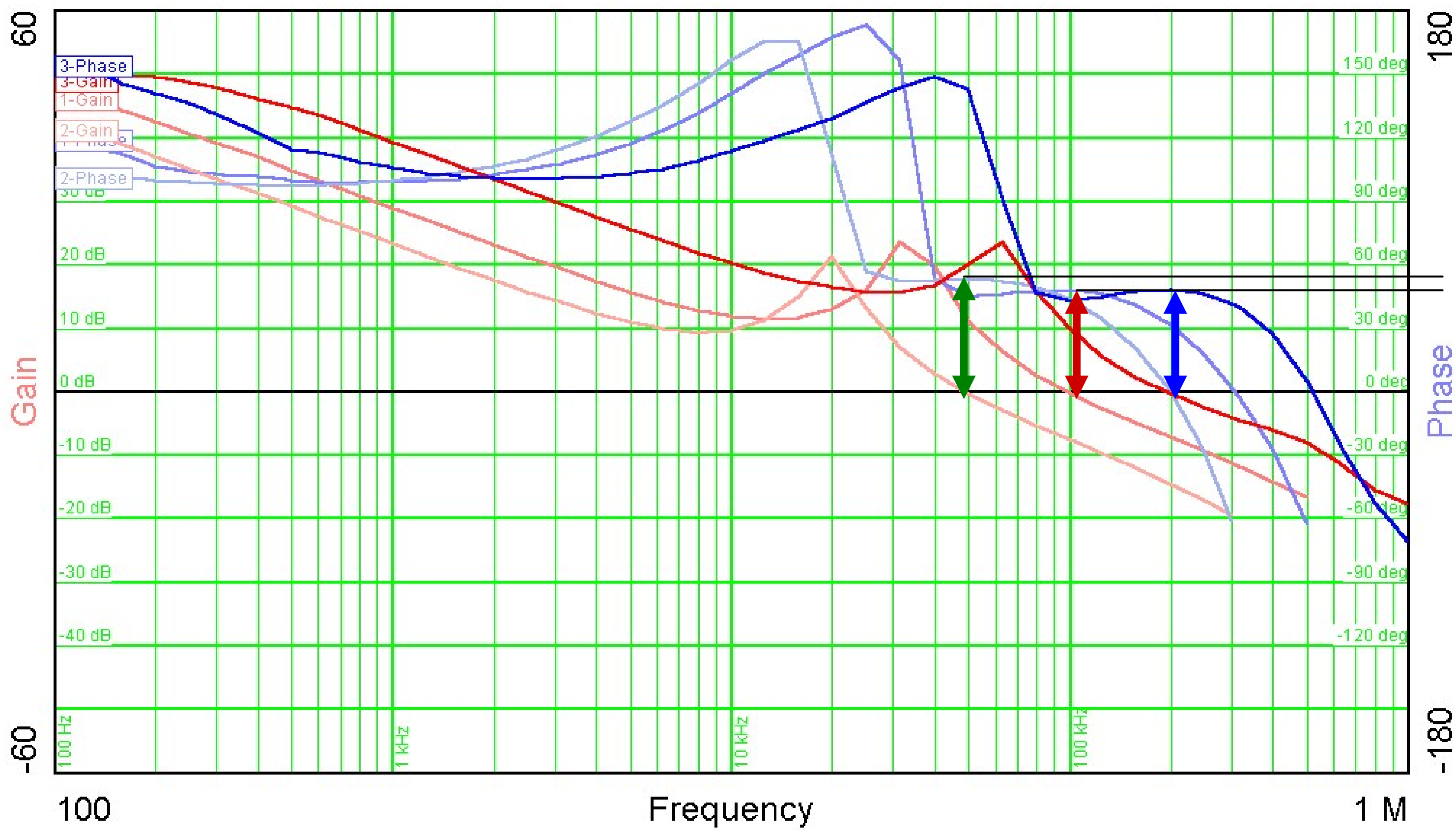
Basic Stability Criterion



Reading Bode Plot

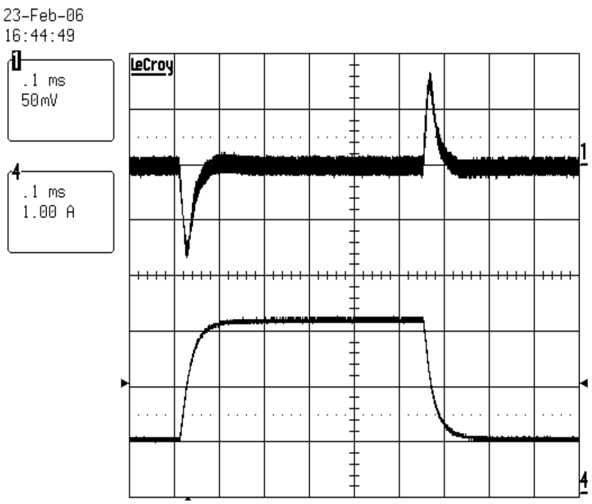
1) Find Cross Over Frequency at 0dB
   - 21 kHz Cross Over
2) Find Phase Margin at the Cross Over Frequency
   - 45° at 21kHz
3) Goal is to have Phase Margin between 45° and 90° to maintain a well-damped transient response

Bode Comparison

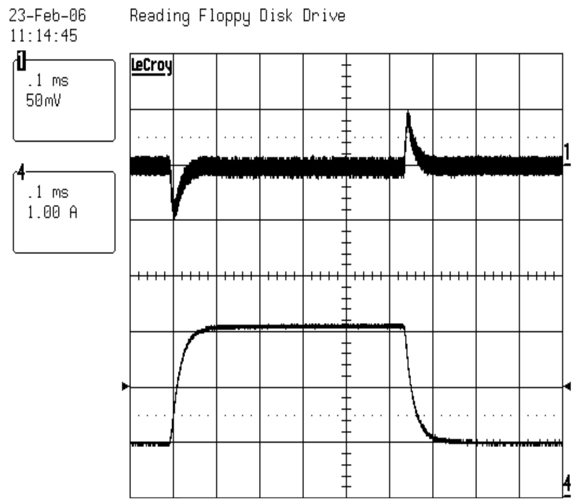


Transient Response

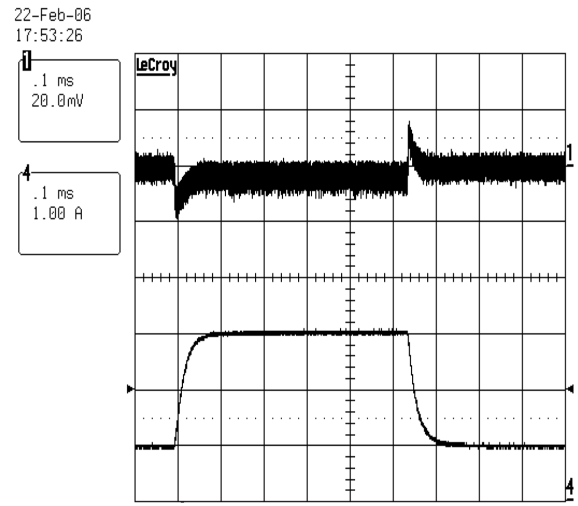
350 kHz



700 kHz



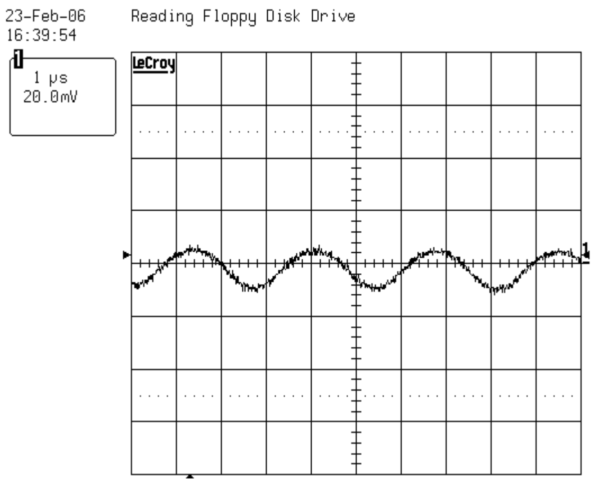
1.6 MHz

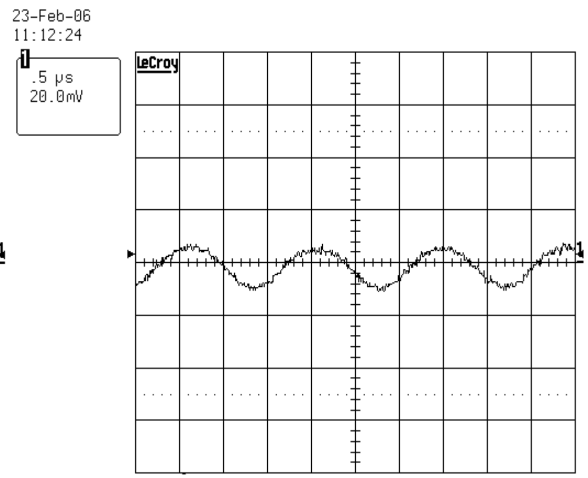


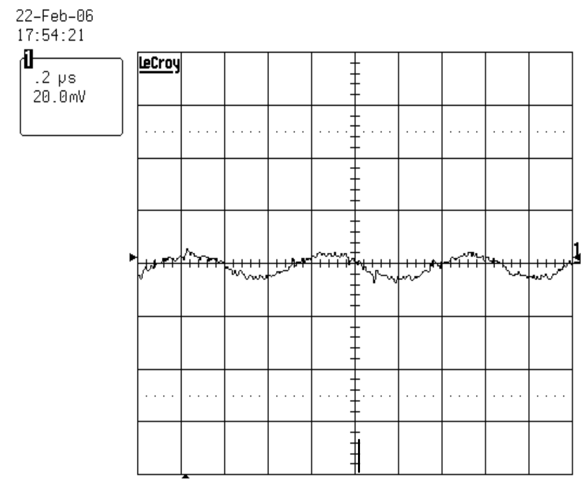
	Cross Over	Phase Margin	Response time	Voltage peak
350kHz	**50kHz**	**52°**	**80us**	**80mV**
700kHz	**95kHz**	**45°**	**70us**	**50mV**
1.6MHz	**200kHz**	**45°**	**60us**	**20mV**

Higher cross-over frequency yields slightly faster transient response

Ripple Comparison







350 kHz
18mV ripple

700 kHz
17mV ripple

1.6 MHz
12mV ripple

Higher switching frequency yields slightly lower output voltage ripple

Competition (>1MHz, >2A)

Part	TPS54317	MAX1536	EL7532	MIC2207	LTC3412A
Current	3-A (4 peak)	3.6-A (4 peak)	2-A	3-A (3.5 peak)	2.5-A (4.5 peak)
Voltage	3 - 6V	3 – 5.5V	2.5-5.5	2.7 - 5.5V	2.7 – 5.5V
Frequency	1.6MHz	1.4 MHz	1.5MHz	2MHz	4MHz
Minimum on time	150ns	300ns	?	?	?
RDS ON	59mΩ	54mΩ	80mΩ	95mΩ	77mΩ
Accuracy	1%	1%	2%	1%	2%
Adj. Soft Start	✓				✓
Enable	✓	✓	✓	✓	✓
Sync Pin	✓				✓
Power Good Pin	✓	✓	✓	✓	✓
Tools Support	✓		✓		✓
Package	4x5/24QFN	5x5/28QFN	10 Pin MSOP	3x3/12SON	4x4/16QFN

TI Power Devices >1MHz

Part Number	Max. Freq.	Iout	Topology	Vin (min)	Vin (max)	Description
TPS62300	3000	0.5	Buck	2.7	6	Adjustable, 500-mA, 3-MHz Step-Down Converter in QFN or Chip-Scale
TPS62320	3000	0.5	Buck	2.7	6	Adjustable, 500-mA, 3-MHz Step-Down Converter in QFN or Chip-Scale
TPS62102	2000	0.5	Buck	2.5	9	Multimode 1MHz Synchronous Buck Converter with Adjustable Output
TPS62220	1850	0.4	Buck	2.5	6	Adjustable, 400-mA, 95% Efficient Step-Down Converter, 15uA, ThinSOT-23
TPS54317	1600	3	Buck	3	6	1.6MHz, 3-6Vin, Synchronous Step Down Converter
TPS62020	1500	0.6	Buck	2.5	6	Adjustable, 600-mA, 95% Efficient Step-Down Converter, 18uA, MSOP-10
TPS62040	1500	1.2	Buck	2.5	6	Adjustable, 1.2-A, 95% Efficient Step-Down Converter, 18uA, MSOP-10
TPS62200	1500	0.3	Buck	2.5	6	Adjustable, 300-mA, 95% Efficient Step-Down Converter in SOT-23
TPS65010	1500	1	Buck	2.5	6	Multi-Channel 1-cell Li-Ion Power Mgmt IC: USB/AC Charger, 2DC/DC, 2 LDOs, I2C interface in QFN-48
TPS40222	1250	1.6	Buck	4.5	8	1.6A, 1.25-MHz Buck Converter in a 3 mm SON Package
TPS60500	1200	0.25	Buck	1.8	6.5	250-mA Adjustable (0.8V-3.3V) High-Efficiency Step-Down Charge Pump

TI Power Devices >1MHz

Part Number	Max. Freq.	Iout	Topology	Vin (min)	Vin (max)	Description
TPS40140	1000	-	Sync. Buck	4.5	15	Dual Channel, Stackable DC/DC Controller
TPS65120	4000		Boost	2.5	5.5	Single-Inductor, Quad-Output Supply for Small Form Factor TFT Display in QFN-16, 3.3-V LDO, Auto-Seq
TPS65140	2100	0.02	Boost, Inverter	2.7	5.5	Triple-Channel, 2.1-A Switch Boost Converter for large LCD displays w/ Power Good in QFN-24
UCC2880x	2000	-	Buck, Boost, Flyback, Forward			High Speed Voltage Mode Pulse Width Modulator
UCC29421	2000	1	Boost, Flyback , SEPIC	1.5	8	High Frequency, Multimode Synchronous Controller
UCC29422	2000	1	Boost, Flyback , SEPIC	1.5	8	High Frequency, Multimode Synchronous Controller
TPS43000	2000	1.25	Boost, Buck, Flyback, SEPIC	1.8	9	Multi-Topology (buck, boost, sepic) High Frequency DC/DC Controller
TPS65130	1500		Boost, Inverter	2.7	5.5	Adjustable, Dual Output, Positive & Negative 800-mA Switch Boost DC/DC 4x4 QFN-24 for OLED,TFT,CCD
TPS65100	1500	0.35	Boost, Inverter	2.7	6	Triple Output TFT LCD Supply w/VCOM Buffer
TPS65105	1500	0.35	Boost, Inverter	2.7	6	TPS65100, TPS65105 - (TFT) LCD Supply with Vcom Buffer
TPS61070	1440	0.15	Boost	0.9	5.5	Adjustable, 600-mA Switch, 90% Efficient PFM/PWM Boost Converter in ThinSOT-23
TPS63700	1380	0.36	Inverter	2.7	5.5	Adjustable, -15V Output Inverting DC/DC Converter in 3x3 QFN
TPS60230	1250	0.125	Boost	2.7	6.5	5-Channel, Current-regulated 125-mA Charge Pump for White LED Backlight in 3x3 QFN

Summary

Minimum on time:

- Vout is limited by the controllable on time and frequency
- Take the input voltage and switching frequency tolerances into consideration
- Check to see if the current limit circuit will respond fast enough

Size

- Switching frequency from 350kHz to 1.6 MHz
  - 50% reduction in filter size, saving only 45mm^2
- Switching frequency from 350kHz to 700kHz
  - 25% reduction in filter size, saving only 21mm^2
- Switching frequency from 350kHz to 1.6MHz
  - Board area from 260mm^2 to 100mm^2, 35% saving on board area
- More heat in a smaller area

Summary

Efficiency

- Efficiency decreases as switching frequency increases mainly due to FET switching losses
- More copper, board area or additional heat-sinking may be needed

Performance

- Higher switching frequency allows for a higher cross over frequency and a faster transient response. Is this necessary?
- High frequency devices are more expensive. Make sure you really need the benefits and can handle the trade offs (heat and efficiency)

Summary

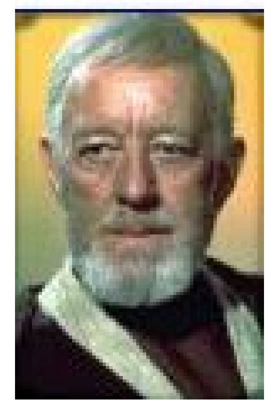
Noise - EMI

- Sometimes an application specific frequency band must be avoided (AM band, ADSL, IF, etc…)
- Alternative - Synchronize the frequency in an area of the band that is not so sensitive
- This topic will be reserved for future study

Jedi Mind Tricks

You must use a higher switching frequency to save space! This new 4MHz part is the ultimate power in the universe – I suggest you use it.

Your sorcerous ways have failed to conjure up the minimum on-time specification in the datasheet. I may save some board space, but there is more heat in that smaller area. The efficiency hit is unacceptable. The transient response is impressive, but not necessary.



Thanks For Considering Texas Instruments!!