Under the Hood of a Multiphase Synchronous Rectified Boost Converter

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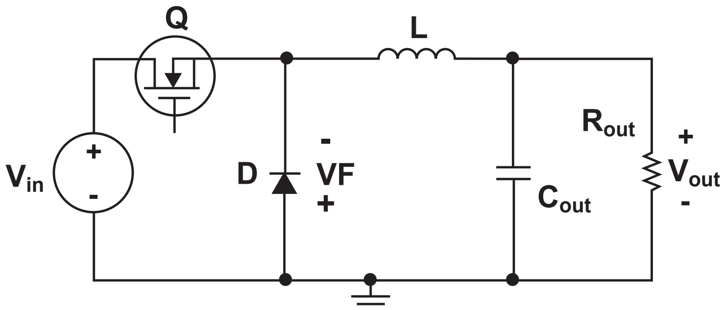
Agenda

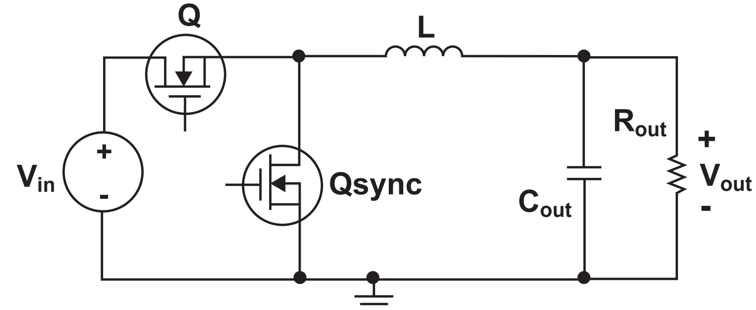
- **Synchronous boost introduction**
  - Deciding how many phases to use
- **Synchronous multiphase boost waveforms**
- **Design example single phase/two phase**
  - Component selection
  - Loss calculations
  - Compensation
- **Results**
- **Summary**

Changing to Synchronous Rectification

Non Synchronous Buck to Synchronous Buck

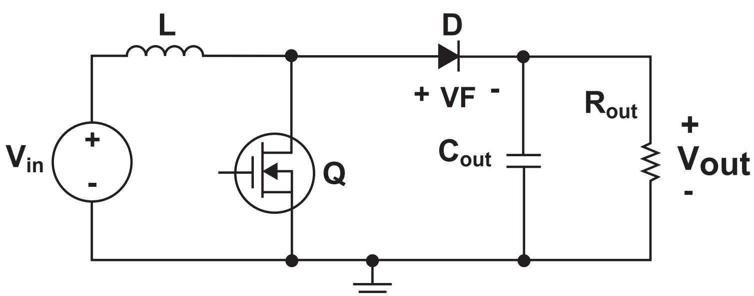


$$\text{Losses} = (1 - D) \times I_{out} \times VF$$

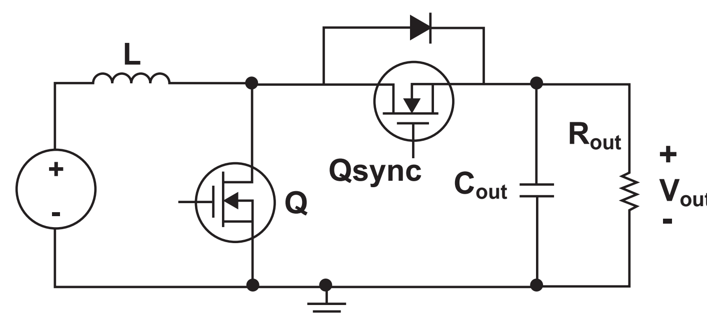


$$\text{Losses} = I_{RMS}^{2} \times RDS_{on}$$

Non Synchronous to Synchronous Boost



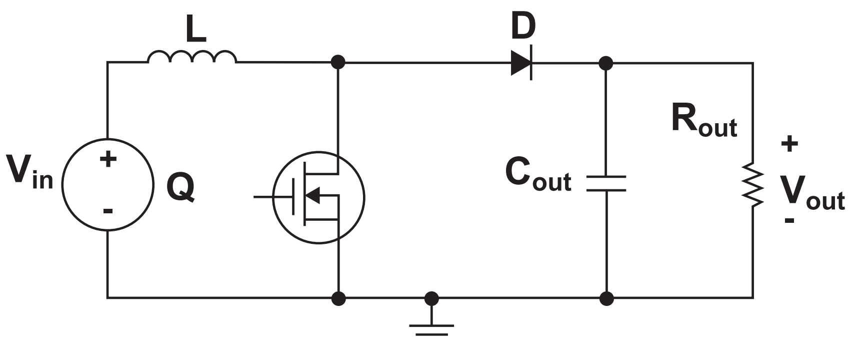
$$\text{Losses} = I_{out} \times V_F$$



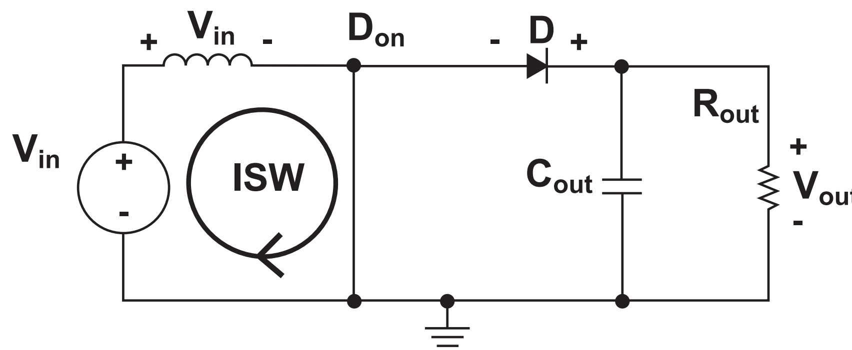
$$\text{Losses} = I_{RMS}^{2} \times RDS_{on}$$

Boost Converter Basic Operation

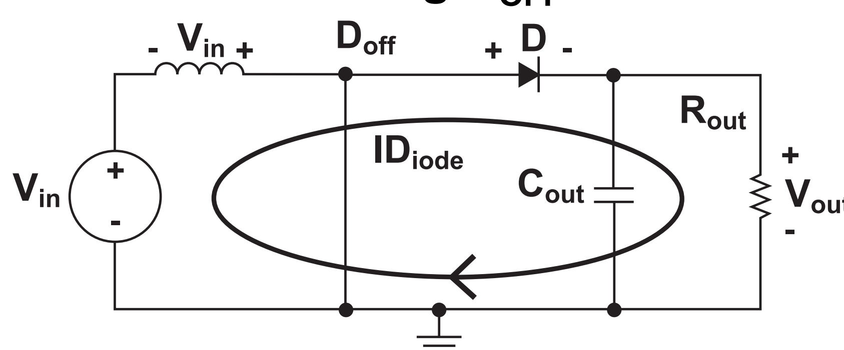
Simple Boost Diagram



Boost During D_{ON} Period

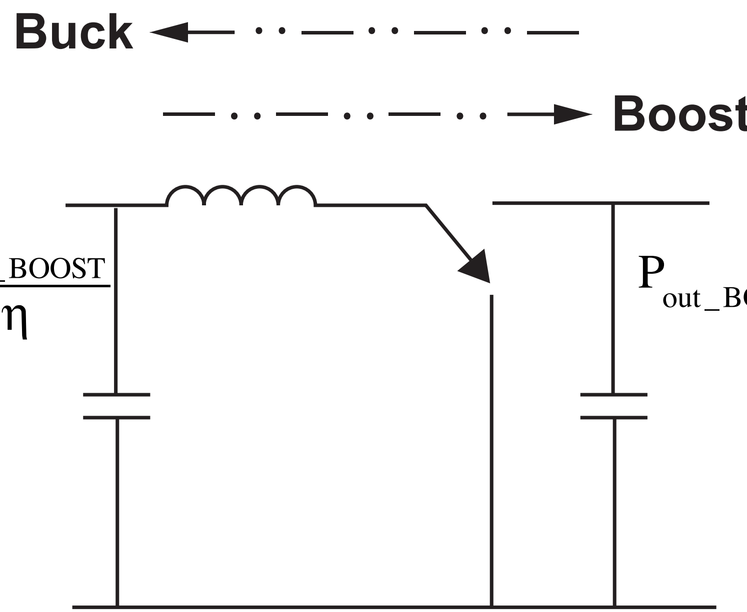


Boost During D_{OFF} Period



Determine Input Current per Phase

Drawing Comparisons Between Buck and Boost



$$P_{in\_BOOST} = \frac{P_{out\_BOOST}}{\eta}$$

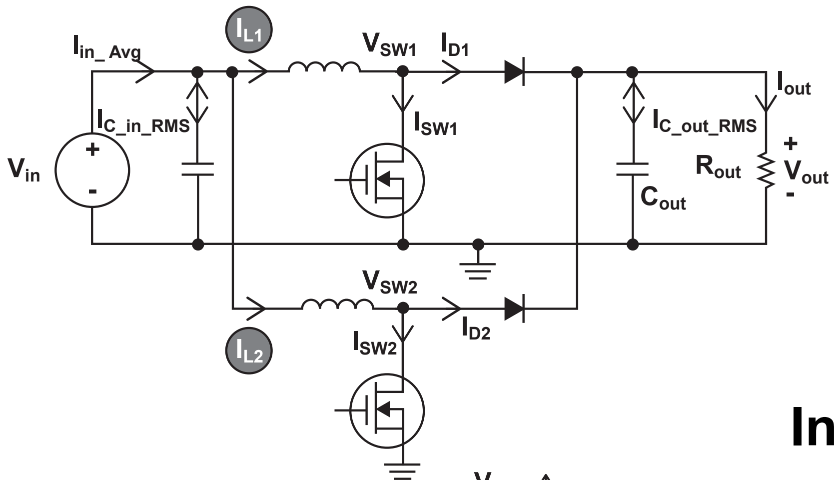
$$P_{out\_BOOST} = V_{out\_BOOST} \times I_{out\_BOOST}$$

$$V_{out\_BUCK} \equiv V_{in\_BOOST}$$

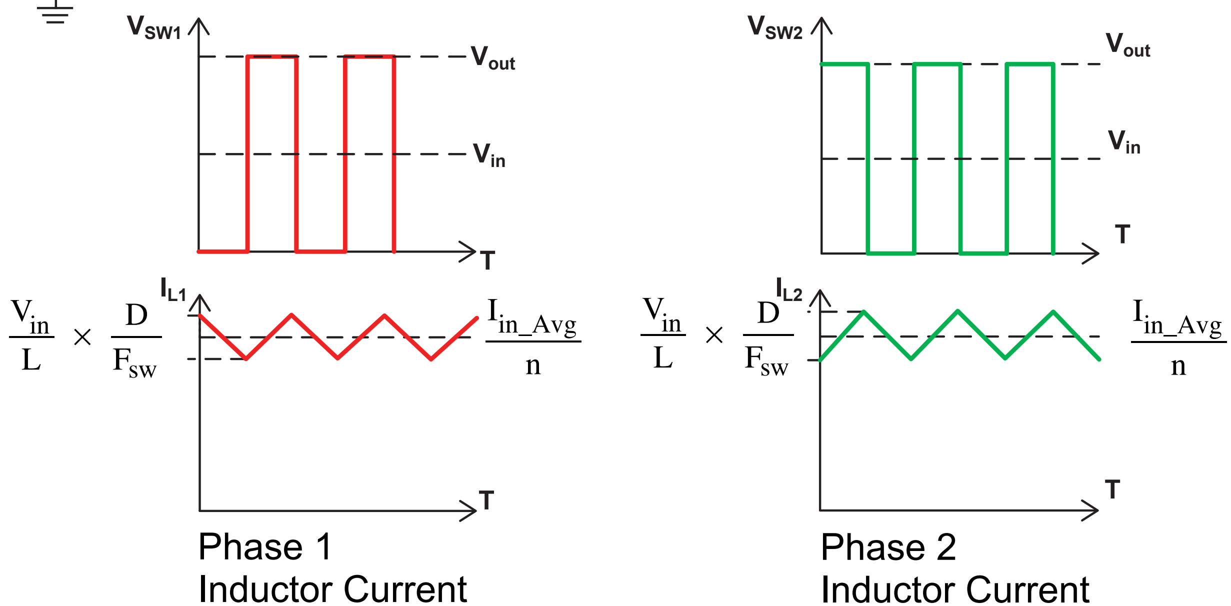
$$I_{out\_BUCK} \equiv V_{in\_BOOST}$$

Canonical Schematic

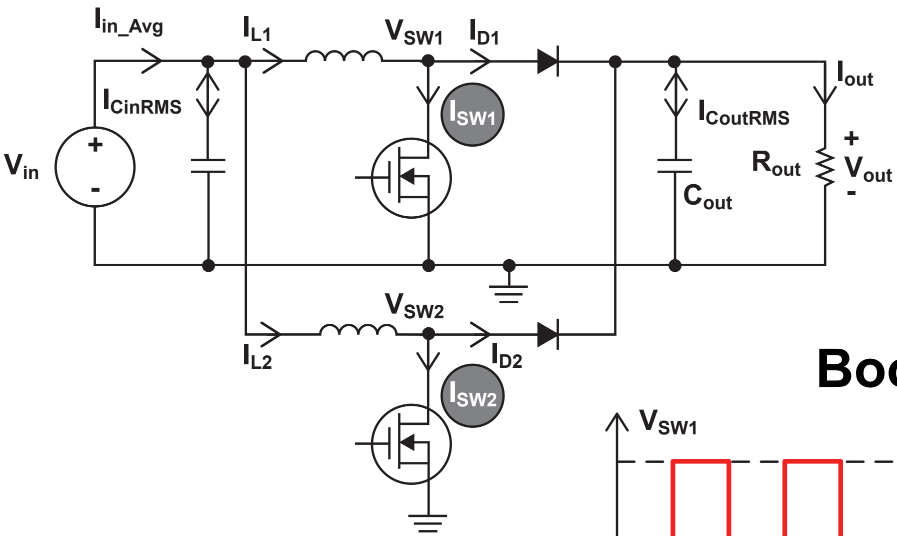
Interleaved Boost Basic Operation



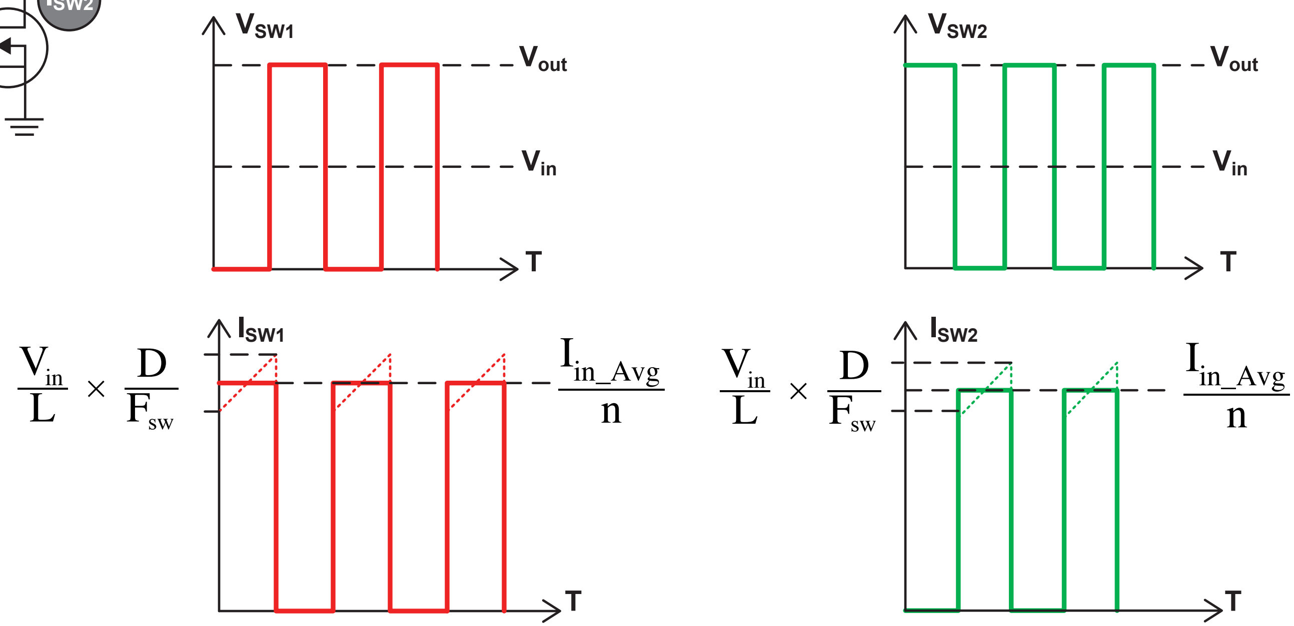
Inductor Currents



Interleaved Boost Basic Operation



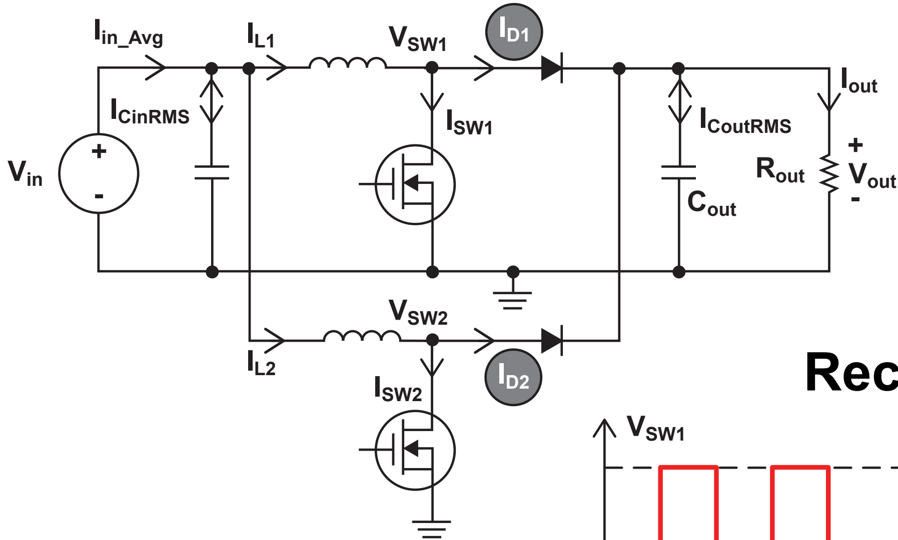
Boost Switch Currents



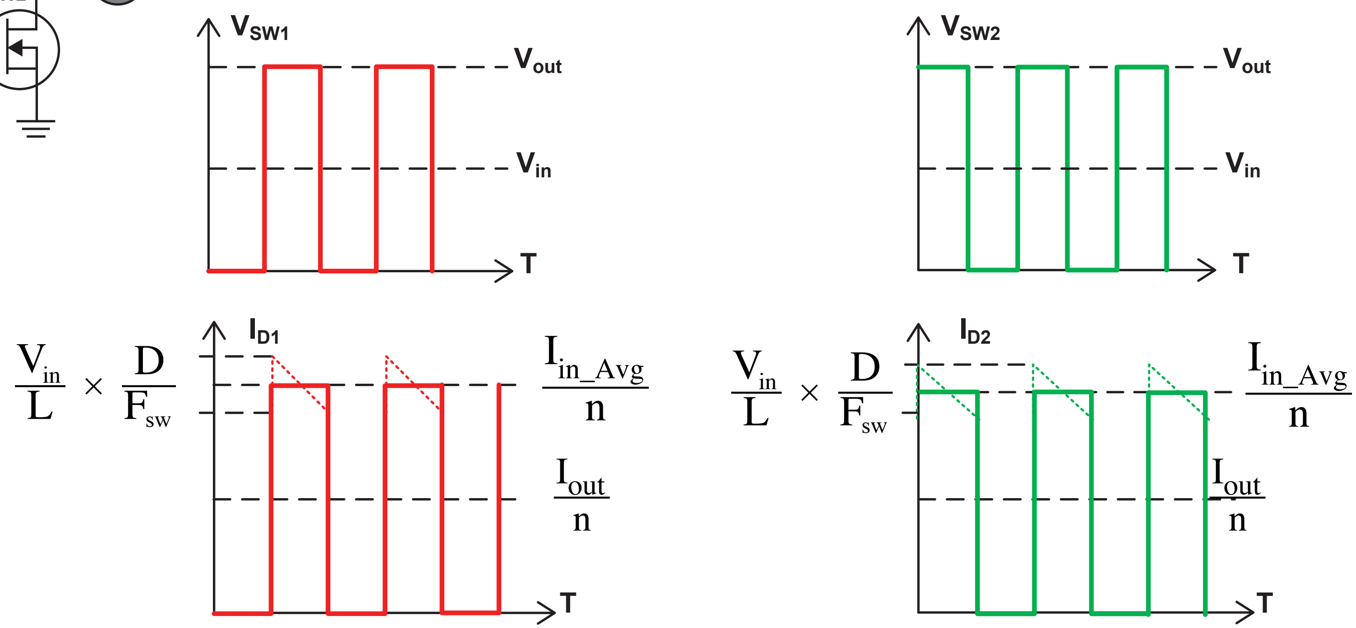
Phase 1 Switch Current

Phase 2 Switch Current

Interleaved Boost Basic Operation



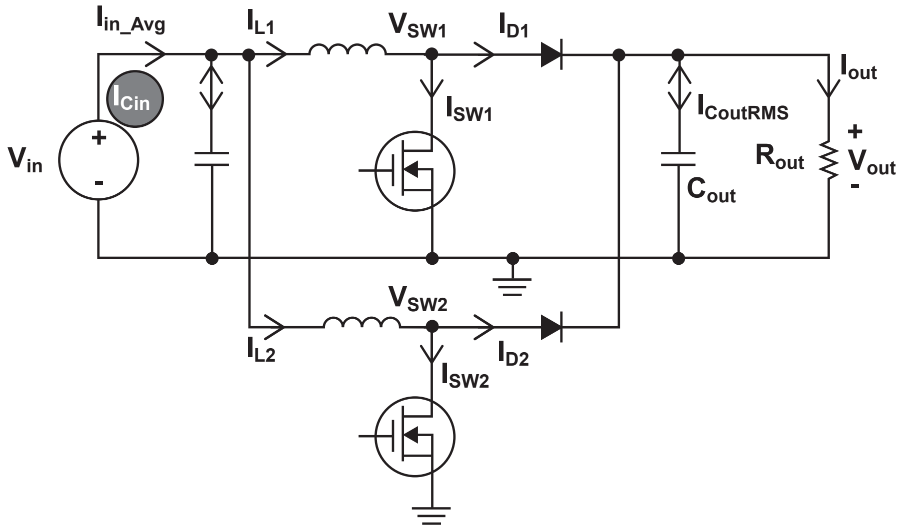
Rectifier Switch Currents



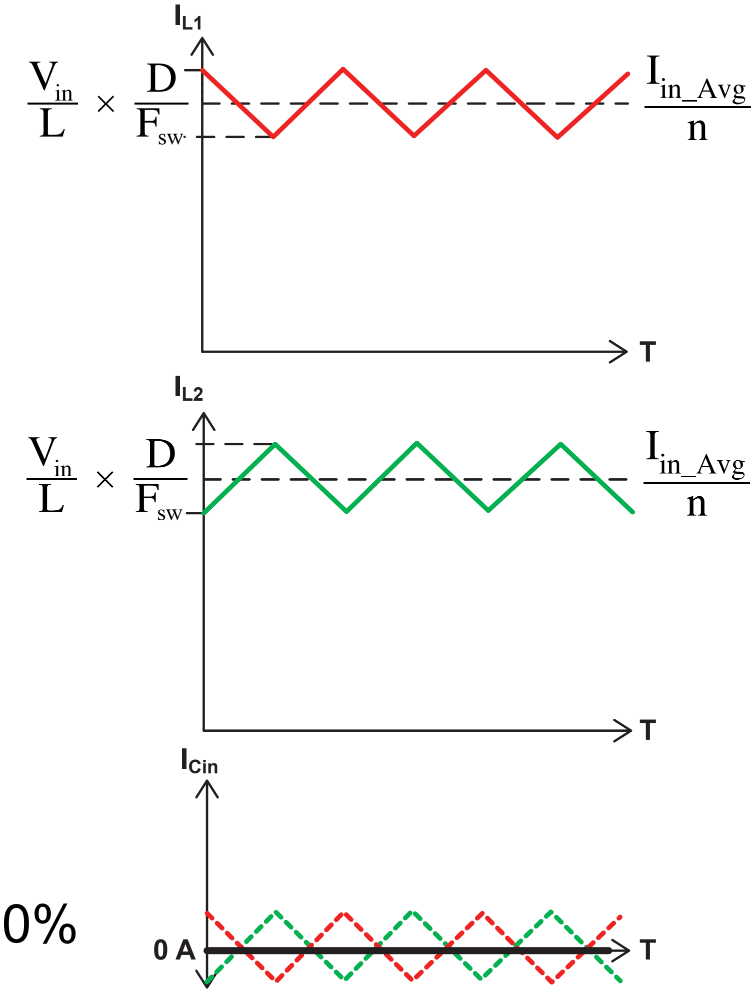
Phase 1 Rectifier Current

Phase 2 Rectifier Current

Interleaved Boost Basic Operation



Input Capacitor Currents



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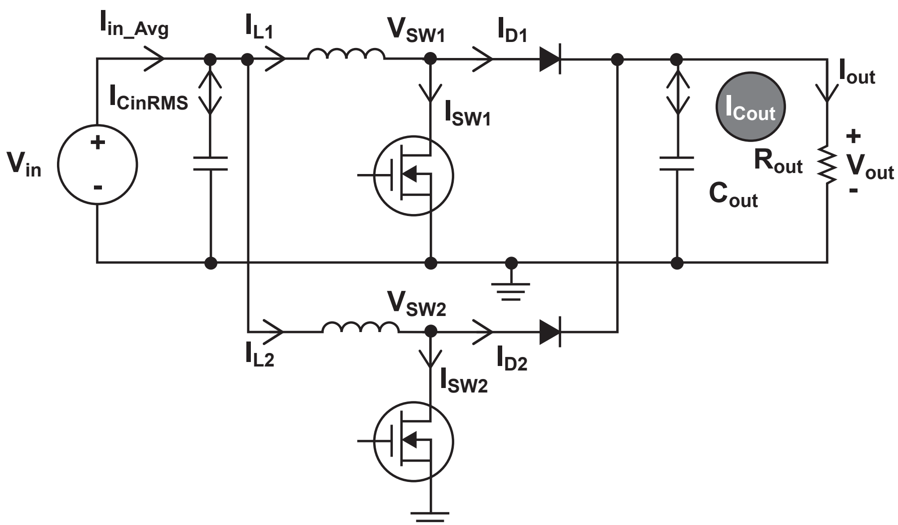
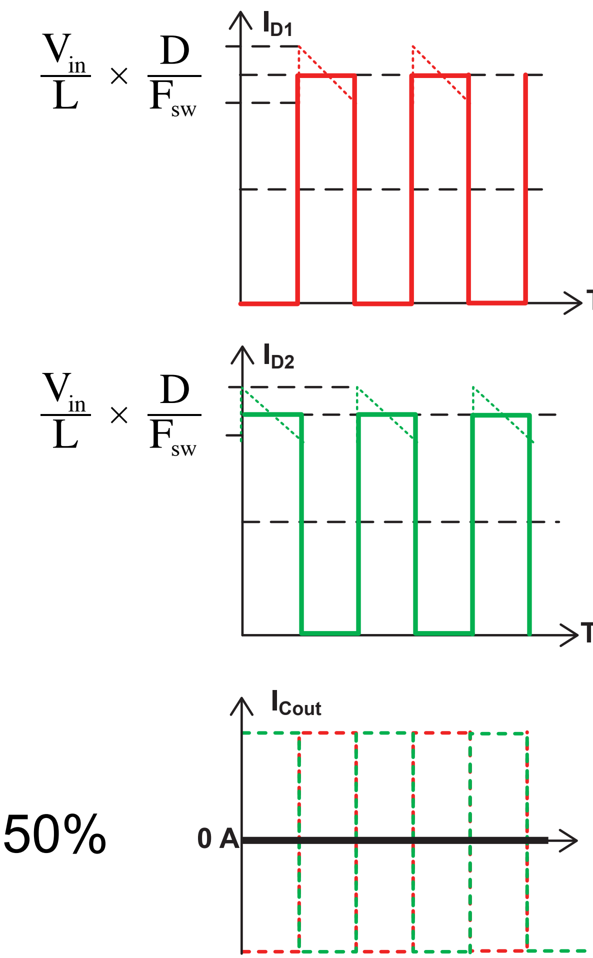
Ripple currents cancel at 50%

Interleaved Boost Basic Operation



Output Capacitor Currents



Ripple currents cancel at 50%

The Basic Boost Calculations

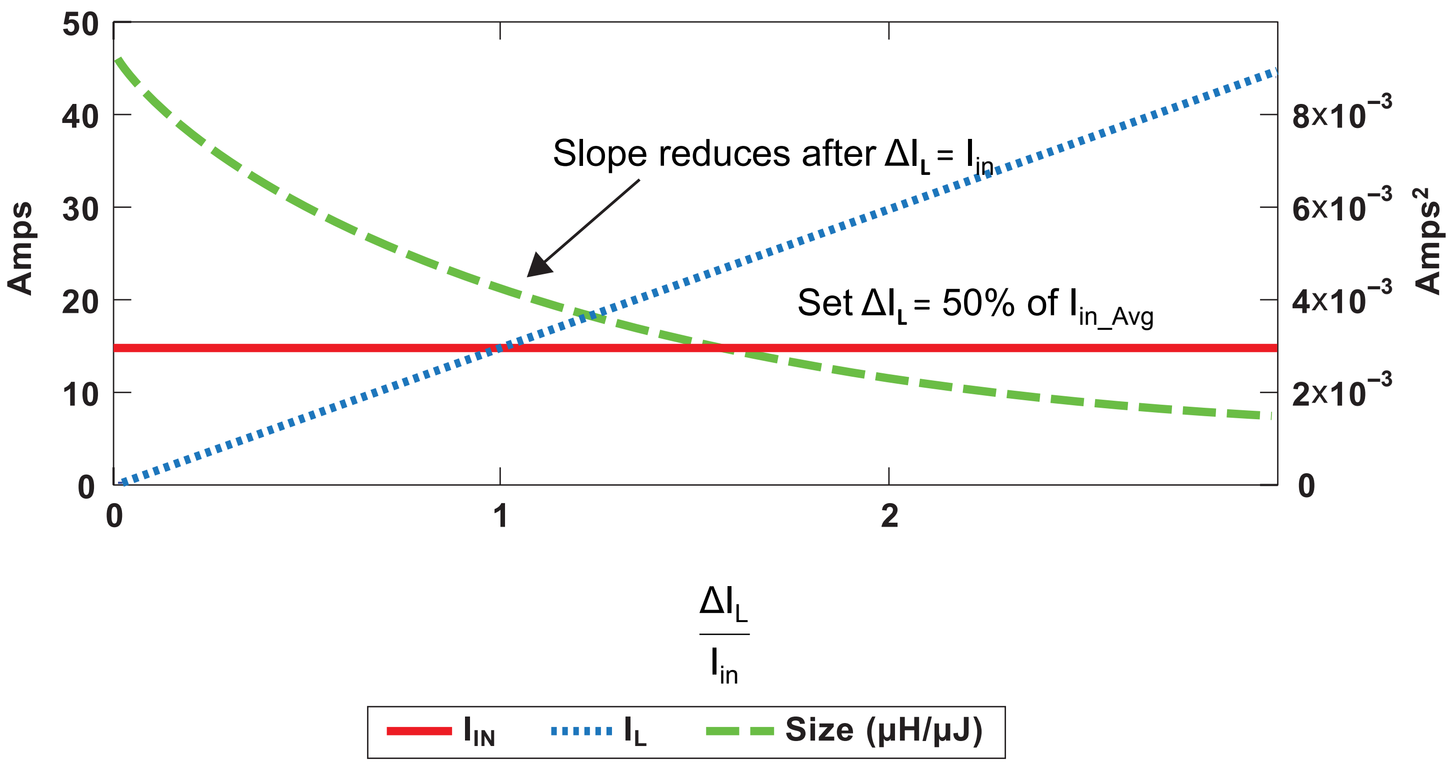
Design Example

- Automotive trunk amplifier
- 14 V_{in}
- 24 V_{out} @ 8 A
- Switching Frequency (F_{sw})
  - 250 kHz (single phase)
  - 125 kHz (two phase) system switching frequency held constant

Equation	Single Phase	Two Phase	Comment
	250 kHz	125 kHz	Per Phase F_{SW}
$\frac{V_{out}}{V_{in}} = \frac{1}{1-D}$	$14.75\ A = \frac{206\ W}{14\ V \times 1}$	$6.8\ A = \frac{206\ W}{14\ V \times 2}$	Transfer Function
$D = \frac{V_{out} - V_{in}}{V_{out}}$	$D = 0.42$	$D = 0.42$	Rearranging for D
$P_{in} = \frac{P_{out}}{\eta}$	$P_{in} = 206\ W$	$P_{in} = 206\ W$	Efficiency Est. 93%
$I_{in\_Avg} = \frac{P_{in}}{V_{in} \times n}$	$14.75\ A = \frac{206\ W}{14\ V \times 1}$	$6.8\ A = \frac{206\ W}{14\ V \times 2}$	$n = \text{No. Phase}$

Selecting the Right Inductor and Inductance Calculations

Graph showing size factor as a function of ΔI_L



Boost Inductor Losses

Equation	Single Phase	Two Phase	Comment
$\Delta I_L = 0.5 \times I_{in\_Avg}$	≈ 7.5 A	≈ 3.5 A	Set ΔI_L to 50% of I_{in_Avg}
$I_{L\_peak} = \frac{\Delta I_L}{2} + I_{in\_Avg}$	= 18.5 A	= 8.4 A	I_{sat} to be set higher than I_{L_peak}
$L = \frac{V_{ind} \times D}{\Delta I_L \times F_{SW}}$	$= 3.16\ \mu H$	$= 13.4\ \mu H$	Boost inductor calculation
$I_{L\_RMS} = \sqrt{I_{in\_Avg}^2 + \left(\frac{\Delta I_L}{\sqrt{12}}\right)^2}$	=14.9 A	= 7A	RMS current for DCR Loss
Selected Inductor	Coilcraft XAL1580-302	Coilcraft SER1390-153	2 cores for the two phase
Inductor size	13.2, 14.1, 7.5	13.5, 13.5, 9	Volume of inductor (in mm³)
DCR	3 mΩ	14 mΩ	
$DCR_{loss} = I_{L\_RMS}^2 \times DCR$	= 0.6 W	= 1.4 W	Total DCR losses
$\text{Coreloss} = K_1 \times f^x \times B^y \times V_E$	= 2.6 W	=18 mW	Total from online calculator

AC Inductor Losses

$$\text{Coreloss} = K_1 \times f^x \times B^y \times V_E$$

- K_1: Constant of the core material
- f: Switching frequency in kHz
  - **Higher frequencies results in higher losses**
- B: Flux density in kGuass
  - **Lower flux density results in lower losses**
- x: Frequency exponent for a specific core material
- y: is the flux exponent for a specific core material
- V_E: Core volume
  - **Larger volume results in more losses**

Boost Convertor MOSFET Considerations

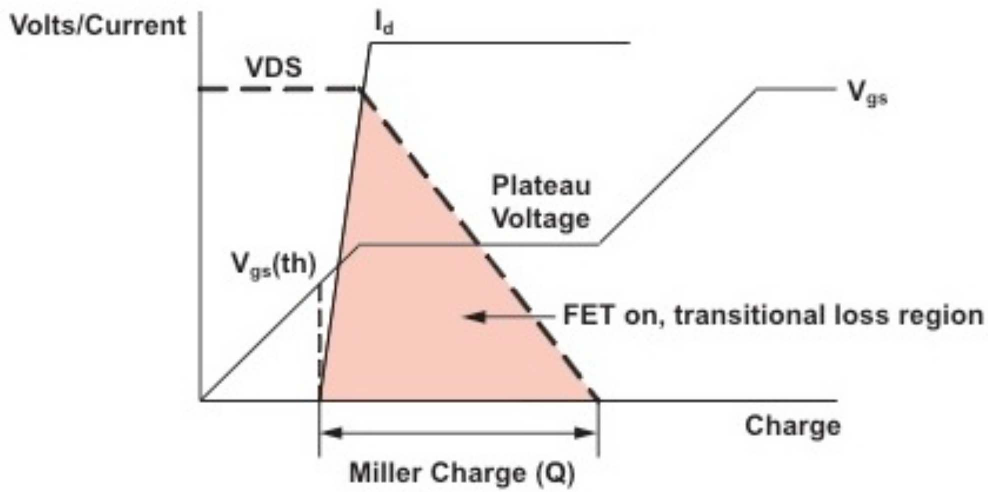
- VDS rating must be greater than output voltage
  - 25% margin is generally acceptable
- Calculate losses to determine suitability
- Losses ideally should be distributed evenly between conduction losses and switching losses
  - Higher RMS currents result in larger conduction losses
  - Higher gate charge results in higher switching losses

Control MOSFET Losses

Equation	Single Phase	Two Phase	Comment
FET Selected	CSD18531Q5A	CSD18531Q5A	RDS_{on}, 3 mΩ, hot 4 mΩ
$I_{FET\_RMS} = \sqrt{D} \times I_{in\_Avg}$	≈ 9 A	≈ 4.47 A	FET RMS current
$FET_{Cond} = I_{FET\_RMS}^2 \times RDS_{on}$	≈ 0.3 W	≈ 0.16 W	Total conduction losses
$SW_{TRANS\_Loss} = V_{in} \times I_{in\_Avg} \times T_{SLEW} \times F_{SW}$	≈ 0.5 W	≈ 0.24 W	Total transitional losses

Control MOSFET Transitional Losses

Transitional Losses at Turn On



$$SW_{TRANSLoss} = V_{in} \times I_{in\_Avg} \times T_{SLEW} \times F_{SW}$$

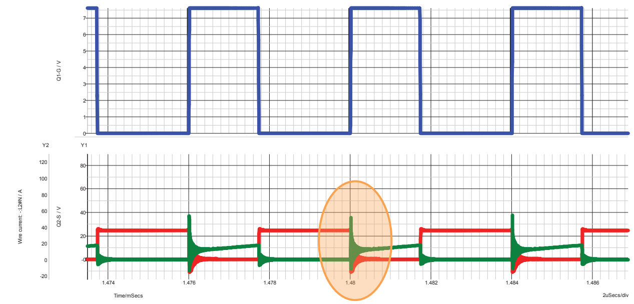
- Use triangular approximation
  - $1/2 \times \text{base} \times \text{height}$
  - For worst case, the "1/2" drops out

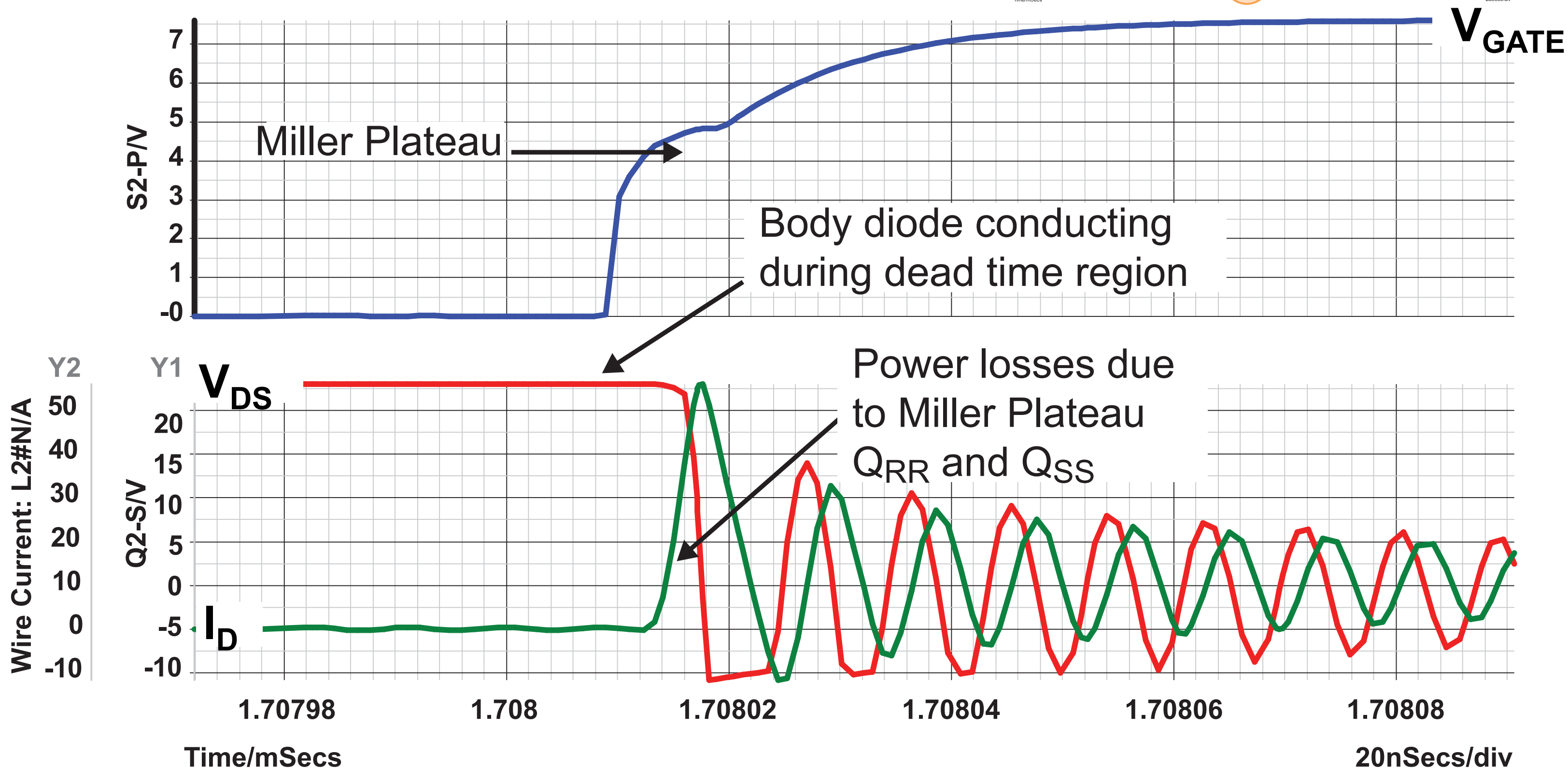
Synchronous MOSFET Losses

Equation	Single Phase	Two Phase	Comment
FET Selected	CSD18531Q5A	CSD18531Q5A	RDS_{on}, 3 mΩ, hot 4 mΩ
$I_{FET\_RMS} = \sqrt{1-D} \times I_{in\_Avg}$	≈ 11.2 A	≈ 5.3 A	FET RMS current
$FETCond = I_{(FET\_RMS)}^{2} \times RDS_{on}$	≈ 0.44 W	≈ 0.22 W	Conduction losses
$Q_{OSSLoss} = \frac{Q_{OSS}}{2} \times V_{out} \times F_{SW} \times n$	≈ 0.2 W	≈ 0.2 W	Q_{OSS} losses for both FETs
$Q_{RR\_Loss} = Q_{RR} \times V_{out} \times n \times F_{SW}$	≈ 0.6 W	≈ 0.35 W	100 nC of Q_{RR} losses in boost FET
$I_{C\_Loss} = V_{in} \times n \times \left\{\left(Q_{Gtot} \times F_{SW}\right) + I_{Q}\right\}$	≈ 0.18 W	≈ 0.33 W	Loss total in IC

Boost Converter FET Switching

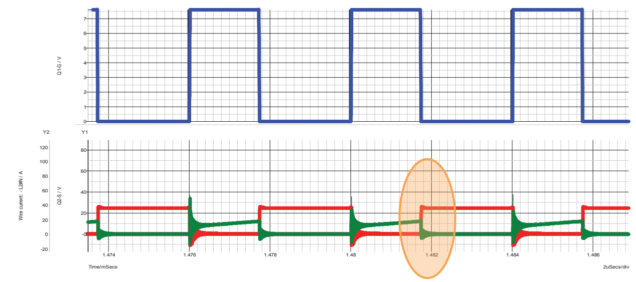
Control FET: Turn On

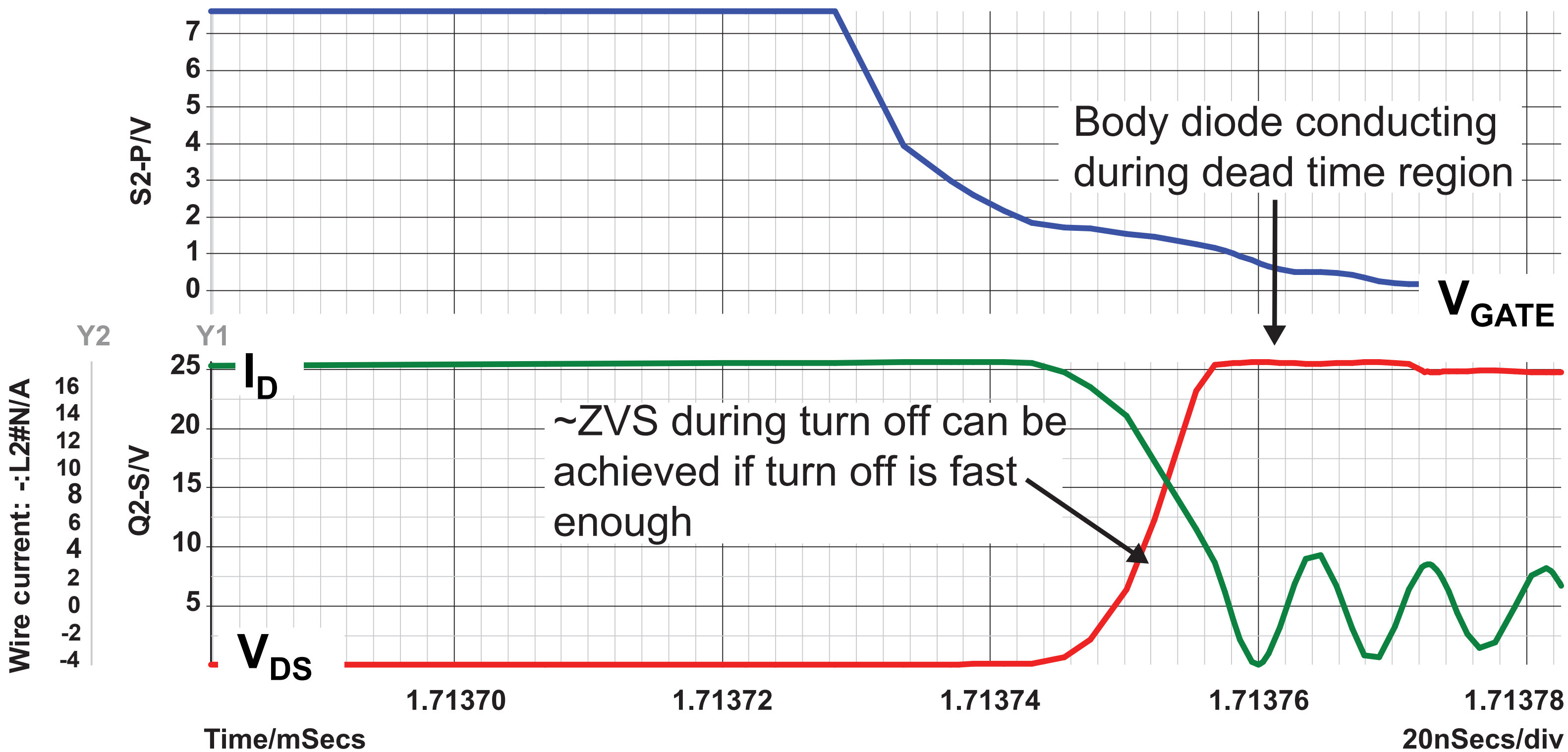




Boost Converter FET Switching

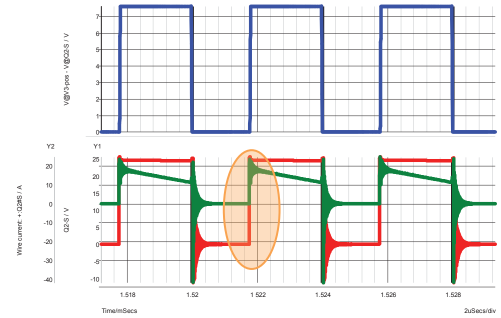
Control FET: Turn Off

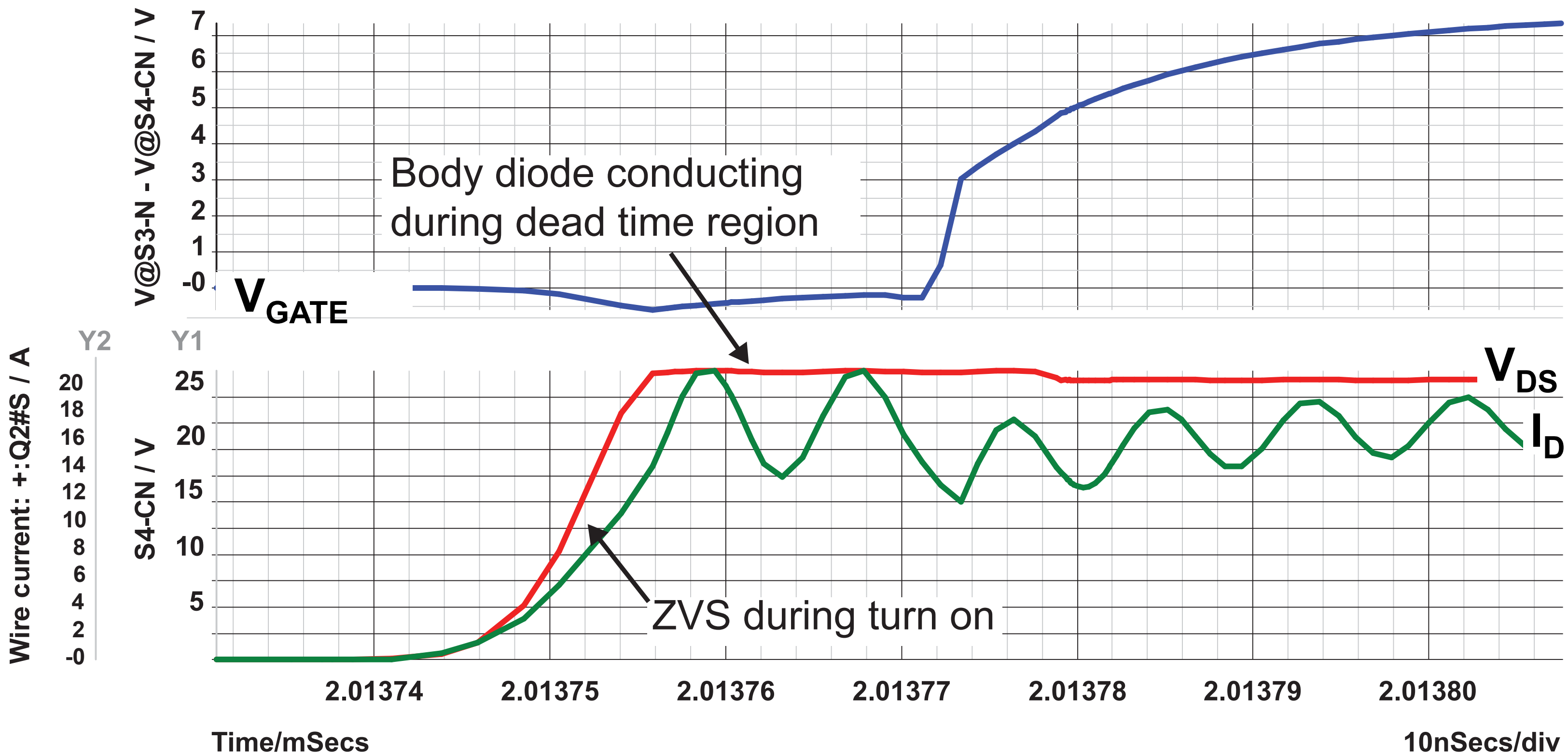




Boost Converter FET Switching

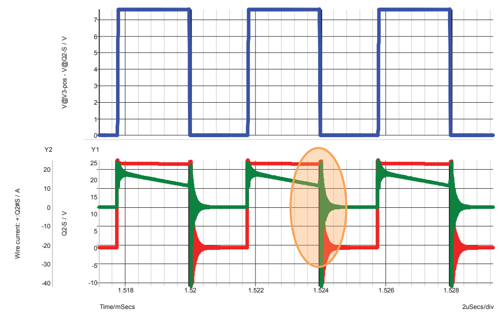
Synchronous FET: Turn On

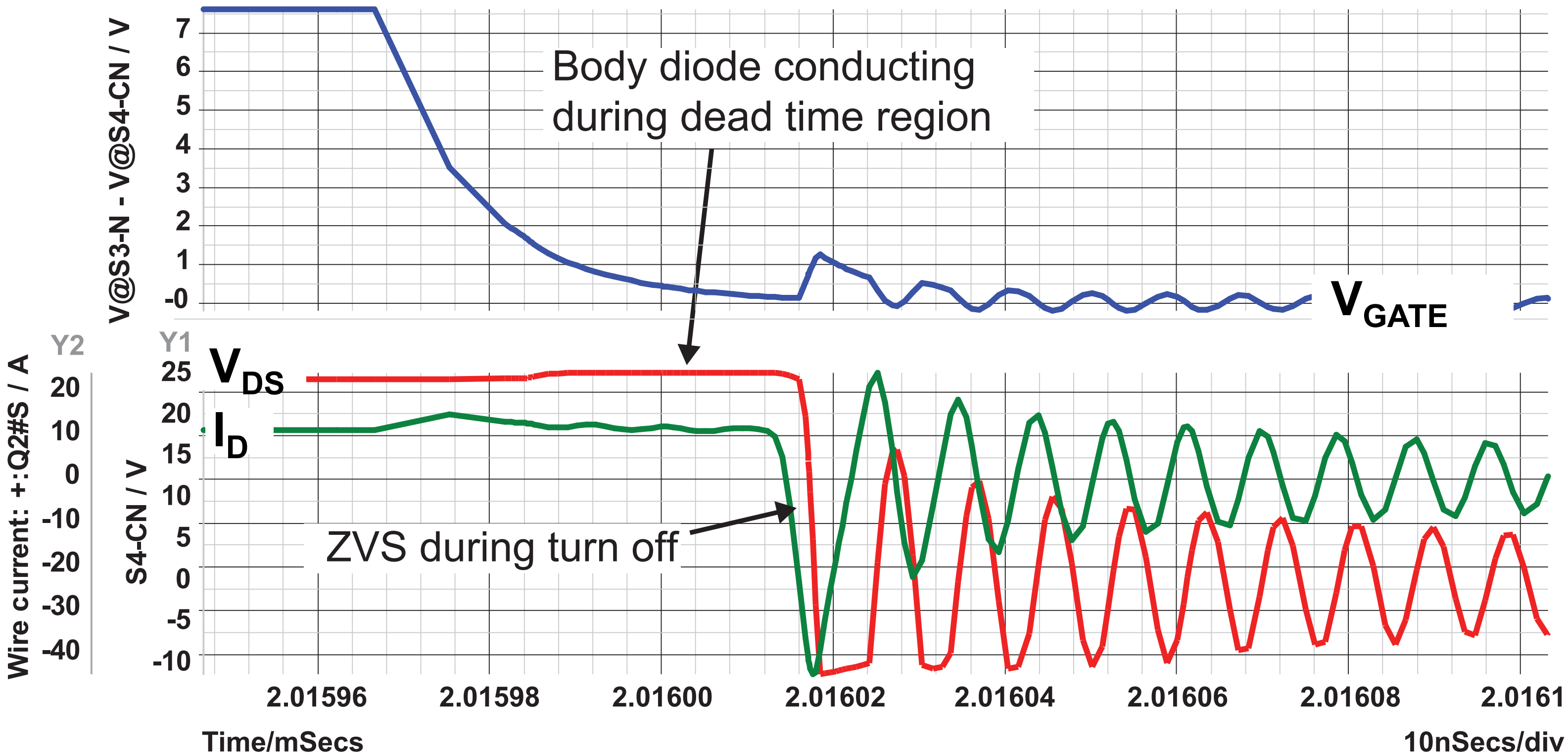




Boost Converter FET Switching

Synchronous FET: Turn Off





Input/Output RMS Ripple Current

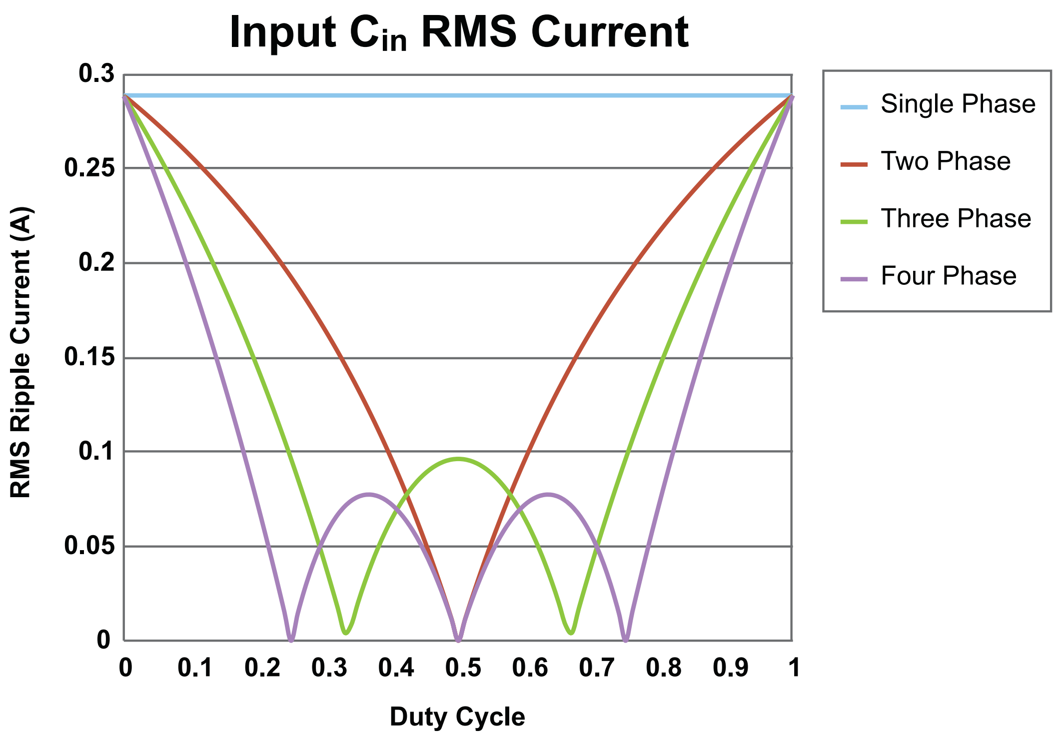
Single Phase	Two Phase	Comment
$I_{C\_in\_RMS} = \frac{\Delta I_L}{\sqrt{12}} = 2.1\ A$	$I_{C\_in\_RMS} = \frac{\Delta I_L}{\sqrt{12}} \times \frac{1-2D}{1-D} = 0.9\ A$	Two phase D < 0.5
$I_{C\_out\_RMS} \approx I_{out} \times \sqrt{\frac{D}{(1-D)}} = 6.7\ A$	$I_{C\_out\_RMS} \approx \frac{I_{out}}{\sqrt{2}} \times \frac{\sqrt{D \times (1-2D)}}{(1-D)} = 2.5\ A$	Two phase D < 0.5
$\Delta I_{C\_out} \approx I_{in\_Avg} = 14.75\ A$	$\Delta I_{C\_out} \approx I_{in\_Avg} = 6.8\ A$	Pk-Pk ripple current in C_{OUT}
1 x PCV1E391MCL2GS	2 x PCV1E391MCL2GS	390 µF electrolytic selected

Output Ripple Voltage Calculations

Single Phase	Two Phase	Comment
$V_{C\_out\_Ripple} = \frac{\Delta I_{C\_out} \times D}{F_{SW} \times C_{out}} = 29\text{ mV}$	$V_{C\_out\_Ripple} = \frac{\Delta I_{C\_out} \times D}{F_{SW} \times C_{out}} = 29\text{ mV}$	Ripple voltage due to charge C_{out}
$\Delta I_{Cout} \approx \frac{I_{out}}{n \times (1 - D)} = 13.7\text{ A}$	$\Delta I_{Cout} \approx \frac{I_{out}}{n \times (1 - D)} = 6.89\text{ A}$	
$V_{C\_out\_Ripple\_ESR} = \Delta I_{C\_out} \times C_{out\_ESR} = 137\text{ mV}$	$V_{C\_out\_Ripple\_ESR} = \Delta I_{C\_out} \times C_{out\_ESR} = 144\text{ mV}$	Ripple voltage due to C_{outESR}
$V_{out\_Ripple} = \sqrt{V_{C\_out\_Ripple}^{2} + V_{C\_out\_Ripple\_ESR}^{2}} = 140\text{ mV}$	$V_{out\_Ripple} = \sqrt{V_{(C\_out\_Ripple)}^{2} + V_{(C\_out\_Ripple\_ESR)}^{2}} = 147\text{ mV}$	Total ripple voltage

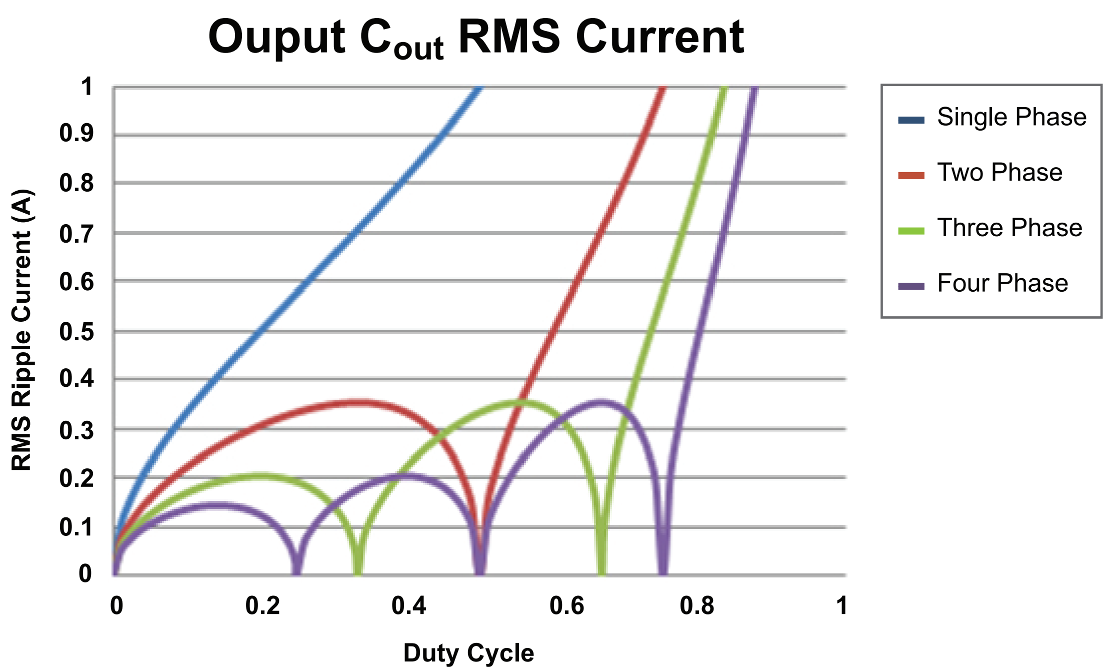
C_{in} RMS Ripple Current Rating Multiphase Boost

- Comparison of ripple current cancelation
- Boost convertor 1, 2, 3 and 4 phase approach
- Using a ΔI_L of 1 A peak to peak



C_{out} RMS Ripple Current Rating Multiphase Boost

- Approximation
- Output ripple current cancelation for a boost convertor
- I_{out} of 1 A using a 1, 2, 3 and 4 phase approach



C_{in} RMS Ripple Current

Condition	Single Phase
$0 < D < 1$	$\frac{\Delta I_L}{\sqrt{12}}$

Condition	Two Phase
$0 < D < 0.5$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{1-2D}{1-D}$
$0.5 < D < 1$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{2D-1}{D}$

Condition	Three Phase
$0 < D < 0.33$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{1-3D}{1-D}$
$0.33 < D < 0.66$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{(1-3D) \times (3D-2)}{3D \times (1-D)}$
$0.66 < D < 1$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{3D-2}{D}$

C_{in} RMS Ripple Current

Condition	Four Phase
$0 < D < 0.25$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{1-4D}{1-D}$
$0.25 < D < 0.5$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{(1-4D) \times (4D-2)}{4D \times (1-D)}$
$0.5 < D < 0.75$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{(3-4D) \times (4D-2)}{4D \times (1-D)}$
$0.75 < D < 1$	$\frac{\Delta I_L}{\sqrt{12}} \times \frac{4D-3}{D}$

C_{out} RMS Ripple Current*

Condition	Single Phase
$0 < D < 1$	$I_{OUT} \times \sqrt{\frac{D}{(1-D)}}$

Condition	Two Phase
$0 < D < 0.5$	$\frac{I_{OUT}}{\sqrt{2}} \times \frac{\sqrt{D \times (1-2D)}}{(1-D)}$
$0.5 < D < 1$	$\frac{I_{OUT}}{2} \times \frac{\sqrt{2 \times (2D-1)}}{\sqrt{1-D}}$

Condition	Three Phase
$0 < D < 0.33$	$\frac{I_{OUT}}{\sqrt{3}} \times \frac{\sqrt{D \times (1\text{-}3D)}}{(1-D)}$
$0.33 < D < 0.66$	$\frac{I_{OUT}}{3} \times \frac{(3D-2) \times (1-3D)}{(1-D)}$
$0.66 < D < 1$	$\frac{I_{OUT}}{3} \times \frac{\sqrt{3D-2}}{\sqrt{1-D}}$

*Approximations

C_{out} RMS Ripple Current*

Condition	Four Phase
$0 < D < 0.25$	$\frac{I_{OUT}}{2} \times \frac{\sqrt{D \times (1-4D)}}{(1-D)}$
$0.25 < D < 0.5$	$\frac{I_{OUT}}{2} \times \frac{\sqrt{(4D-2) \times (1-4D)}}{2 \times (1-D)}$
$0.5 < D < 0.75$	$\frac{I_{OUT}}{2} \times \frac{\sqrt{(4D-2) \times (3-4D)}}{2 \times (1-D)}$
$0.75 < D < 1$	$\frac{I_{OUT}}{2} \times \frac{\sqrt{4D-3}}{\sqrt{1-D}}$

*Approximations

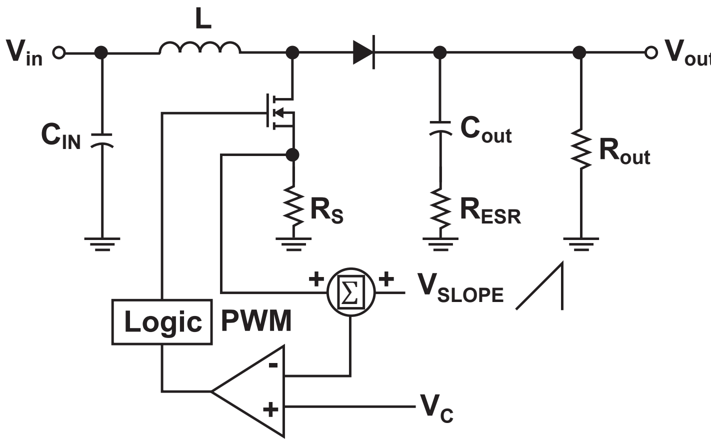
Loop Stability of a Current Mode Boost

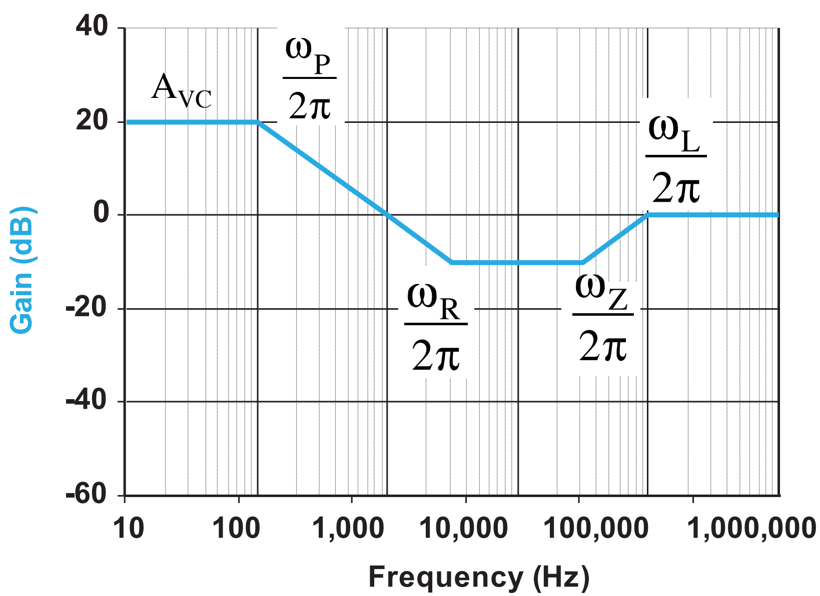
- Current mode control modifies the complex conjugate double pole to two separate poles
  - The inductor pole pushes to a higher frequency
- Typically use current mode control due to the Right Half Plane Zero (RHPZ)
  - RHPZ causes sudden decrease in the 1-D period due to control loop increasing D for sudden load step
  - Adds additional phase drop of negative 90^{o} phase shift
- Cross over frequency below RHPZ frequency to avoid additional phase shift
- For current mode control, duty cycles approaching 0.5 and beyond require modification to the current sense to avoid subharmonic oscillation

Loop Stability of a Dual Phase Current Mode Boost

- Adjustments to accommodate an interleaved configuration
- Divide down the output capacitor by number of phases
  - C_{out} becomes 195 µF from 390 µF
- Multiply the output capacitor ESR by number of phases ESR
  - ESR becomes 40 mΩ, from 20 mΩ
- Multiply R_{out} by number of phases
  - R_{out} becomes 6 ohm from 3 Ω
  - All other elements stay the same

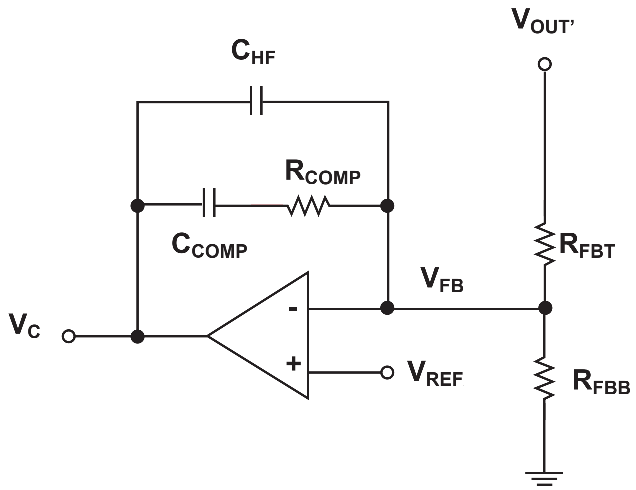
Current Mode Boost Power Stage

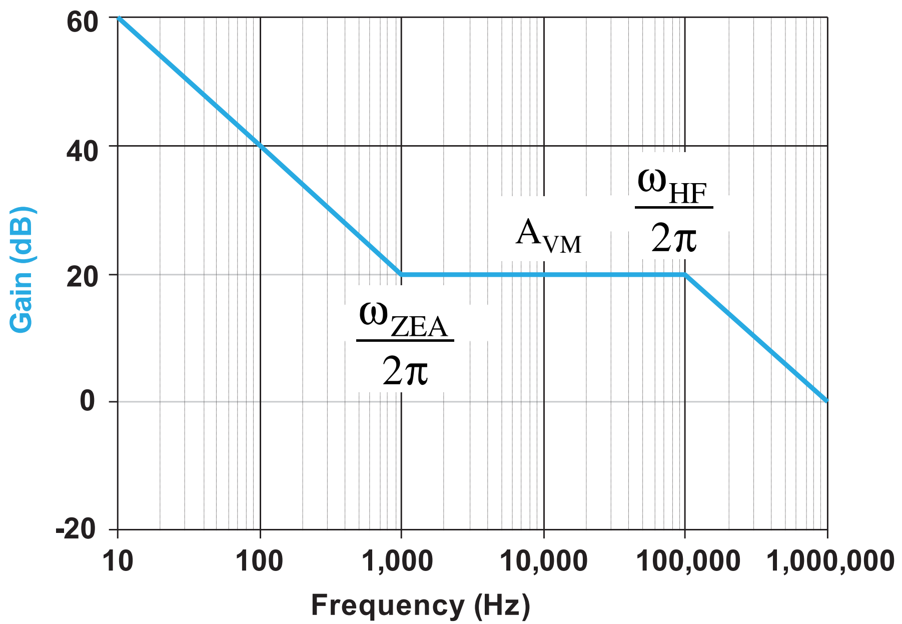




Variable	Equation
$\frac{\hat{V}_{OUT}}{\hat{V}_C}$	$AVC \times \frac{\left(1-\frac{s}{\omega_R}\right)\times\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_P}\right)\times\left(1+\frac{s}{\omega_L}\right)}$
R_I	$A_{CS} \times R_S$
A_{VC}	$\approx R_{out} \times n \times \frac{(1-D)}{2 \times R_I}$
ω_P	$\approx \frac{2}{C_{out} \times R_{out}}$
ω_L	$= \frac{K_M \times R_I}{L}$
K_M	$\approx \frac{V_{out}}{V_{SLOPE}}$
ω_Z	$= \frac{1}{C_{out} \times R_{ESR}}$
ω_R	$= \frac{R_{out} \times n \times (1 - D)^2}{L}$
V_{SLOPE}	$\frac{(V_{out} - V_{in}) \times R_i}{L \times f_{SW}}$

Type II Error Amplifier

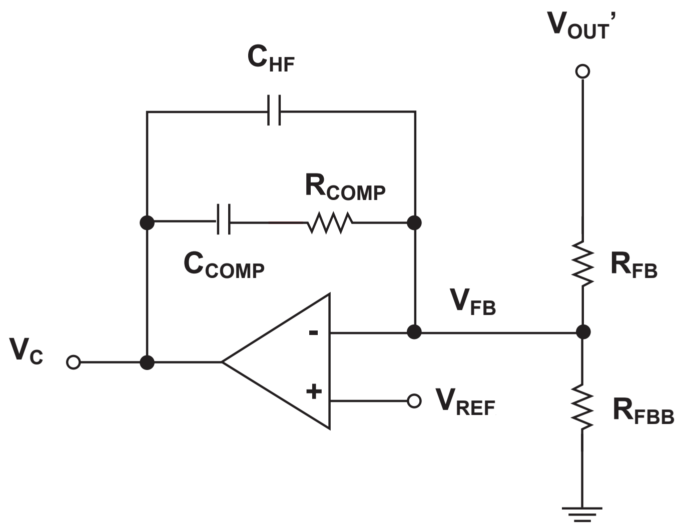




$$\frac{\omega_{ZEA}}{2\pi} = \frac{\omega_C}{2\pi \times 10}$$

$$\frac{\omega_{HF}}{2\pi} = \frac{\omega_R}{2\pi}$$

Type II Error Amplifier



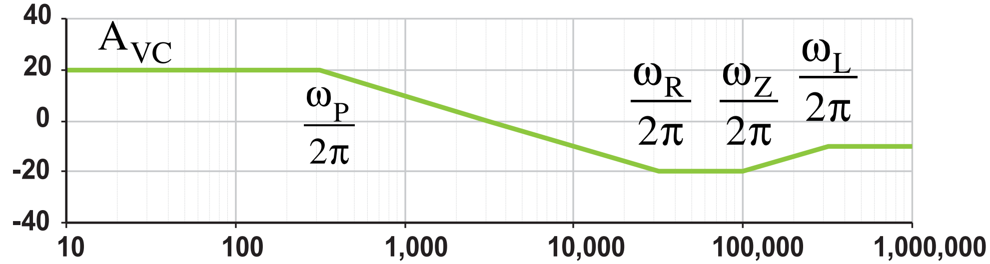
Variable	Single Phase	Two Phase	Comment
R_{FBT}	10 kΩ	10 kΩ	Choose value between 2 kΩ 100 kΩ
D_{MAX}	$= 0.625$	$= 0.625$	$= \frac{V_{out} - V_{in\_Min}}{V_{out}}, V_{in\_Min} = 9V$
R_I	= 40 mΩ	= 80 mΩ	$A_{CS} \times R_S$
G_{M_Mod}	$= 9.375$	$= 4.688$	$= \frac{1 - D_{max}}{R_I}$

Boost Compensation Approach

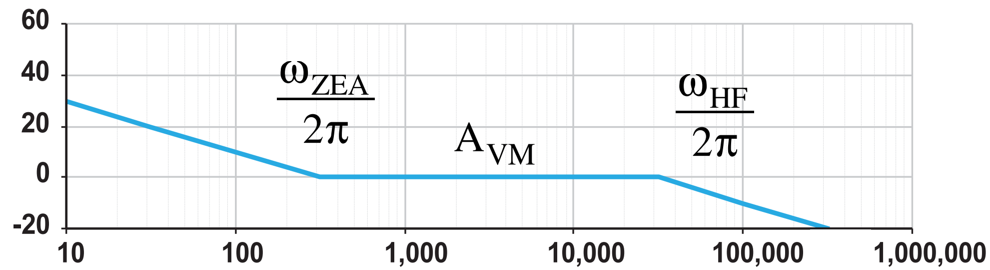
Variable	Single Phase	Two Phase	Comment
RHPZ	$\approx 52\ \text{kHz}$	$\approx 21\ \text{kHz}$	$= \dfrac{R_{out} \times n \times (1-D)}{L \times 2\pi}$
F_C	$\approx 12.5\ \text{kHz}$	$\approx 5\ \text{kHz}$	$= \dfrac{\text{RHPZ}}{4}$
ω_C	$\approx 12.5\ \text{kHz} \times 2\pi$	$\approx 5\ \text{kHz} \times 2\pi$	$= \dfrac{\omega_R}{4}$
A_{VM}	$= 4.4$	$= 1$	$= \dfrac{\omega_C \times \dfrac{C_{out}}{n}}{G_{M\_Mod}}$
R_{COMP}	$= 44\ \text{k}\Omega$	$= 10\ \text{k}\Omega$	$= A_{VM} \times R_{FBT}$
C_{COMP}	$\approx 2.8\ \text{nF}$	$\approx 27\ \text{nF}$	$C_{COMP} = \dfrac{1}{R_{COMP} \times \omega_{ZEA}}$
C_{HF}	$\approx 68\ \text{pF}$	$\approx 720\ \text{pF}$	$C_{HF} = \dfrac{1}{R_{COMP} \times \omega_{HF}}$

Asymptotic

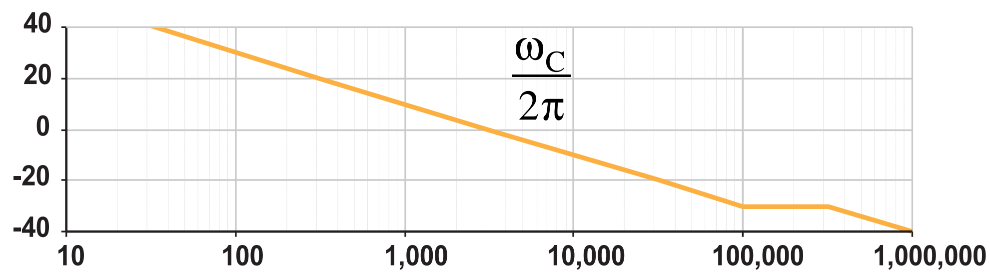
Power Stage Current Mode Boost



Type II Error Amplifier



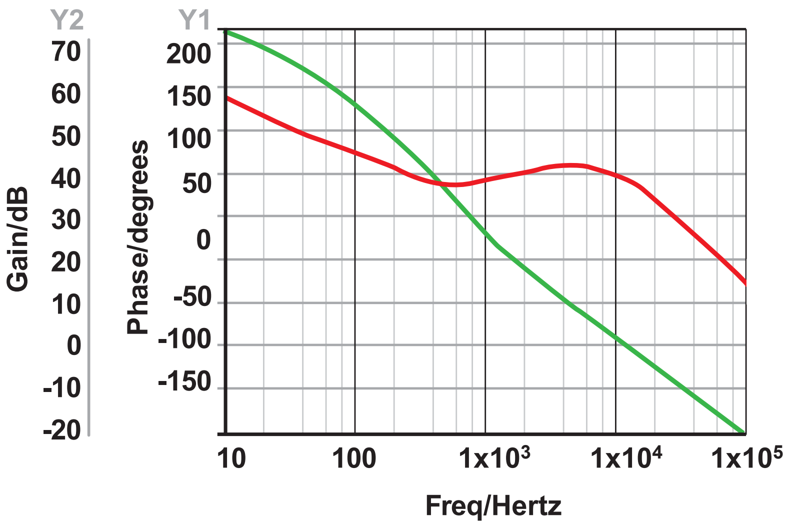
Control Loop



Compensation Results Single Phase

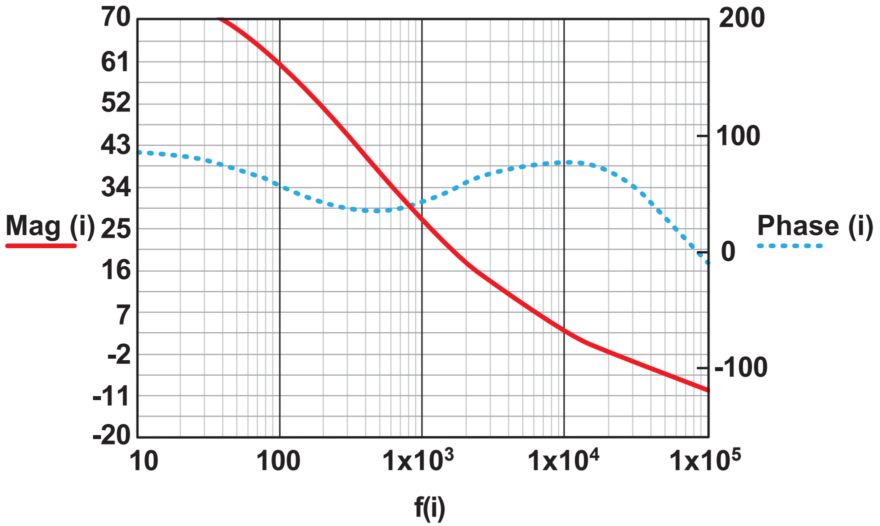
Simulation results

- A crossover frequency of ~13 k and a PM of ~50 degrees



MathCAD results

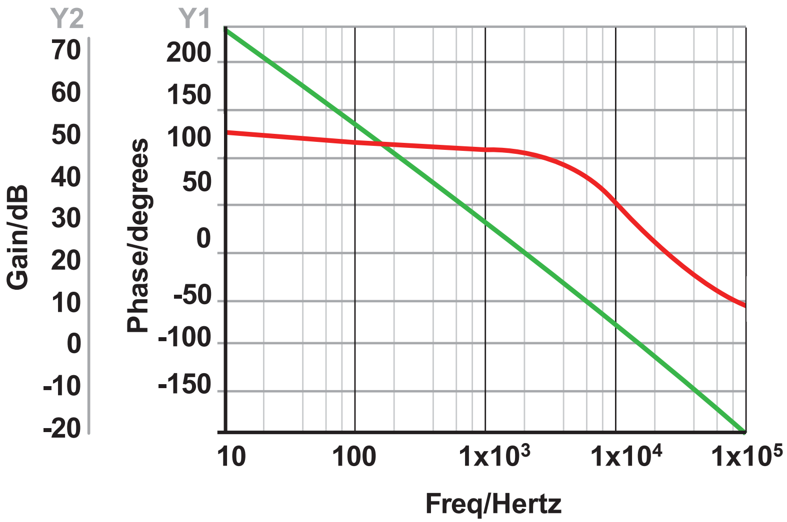
- F_C of ~13 k and a PM of ~75 degrees



Dual Phase Compensation Results

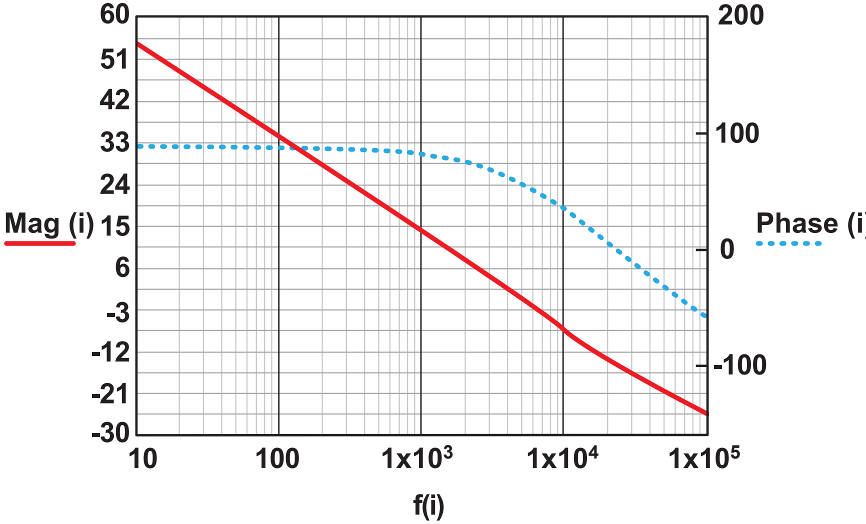
Simulation results (Simplis)

- Shows an F_C of ~5 kHz and a PM of ~56 degrees



Mathcad results

- Mathcad result correlate well to simulation showing an Fc of ~5 kHz and a PM of ~60 degrees



Summary of Results

Parameter	Single Phase	Dual Phase
Per phase switching frequency	250 kHz	125 kHz
Inductance value	3 µH	15 µH
I_{sat}	15 A	9 A
Energy 1/2 x L x I^2	**337.5 µJ**	**1.215 mJ**
Inductor DCR losses	0.6 W	1.4 W Total
Inductor core losses	2.6 W	0.018 W Total
R_{sense}	4 mΩ	8 mΩ
R_{sense} losses	0.9 W	0.8 W Total
Boost FET conduction losses	0.3 W	0.16 W Total
Boost FET transitional losses	0.525 W	0.25 W Total
FET Q_{OSS} losses	0.2 W	0.2 W Total
Q_{RR} losses	0.35 W	0.35 W
Synchronous FET conduction losses	0.44 W	0.22 W
I_C losses	0.182 W	0.336 W
Total losses	**6.097 W**	**3.724 W**
Calculated efficiency	**~97%**	**~98%**
C_{in} RMS ripple current rating	2.1 A	0.9 A
C_{out} RMS ripple current rating	6.7 A	2.5 A
C_{in}	22 µF	22 µF
C_{out}	780 µF	390 µF
F_C	**12.5 kHz**	**5 kHz**

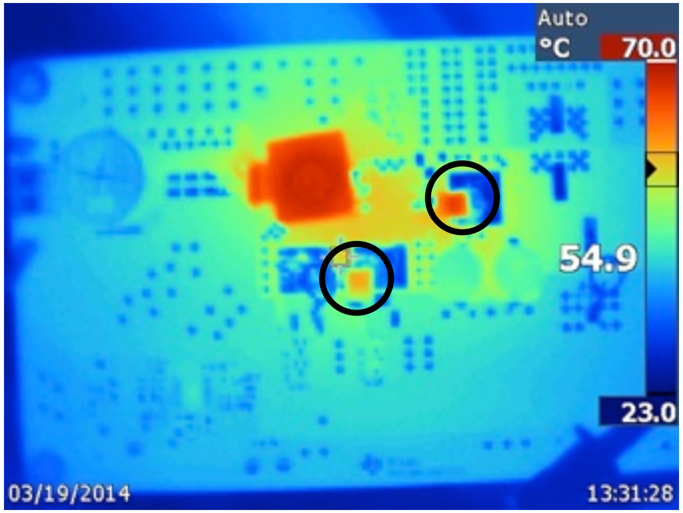
Summary of Results

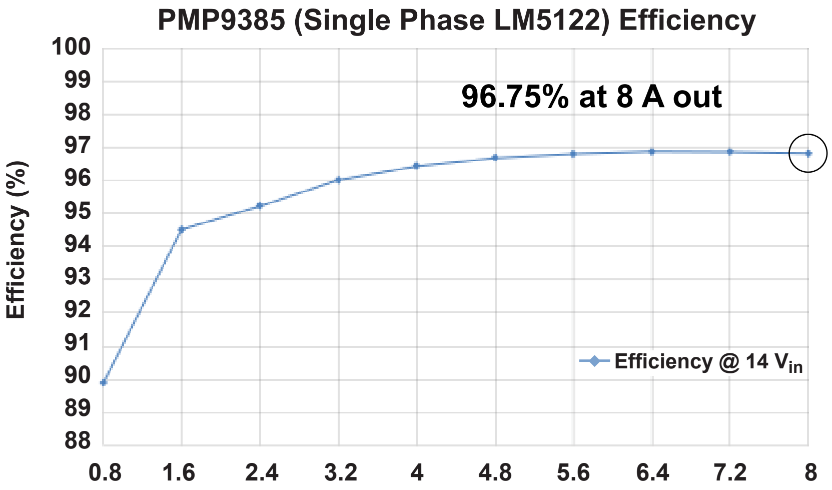
Component Count Comparison

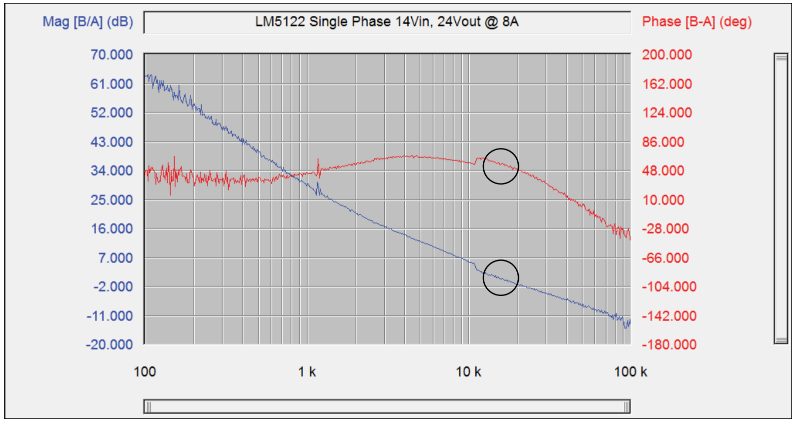
	Part Number	Single Phase	Part Number	Dual Phase
MOSFETs	CSD18531Q5A	2	CSD18531Q5A	4
C_{in}	25 V Ceramic	1	25 V Ceramic	1
C_{out}	PCV1E391MCL2GS	2	PCV1E391MCL2GS	1
Inductor	XAL1580-302	1	SER1390-153	2
IC	LM5122	1	LM5122	2
R_{sense}	2 W Current Sense	1	2 W Current Sense	2
Total		**8**		**12**

Bench Test Results: Single Phase (PMP9385)

Efficiency and Thermals Comparison



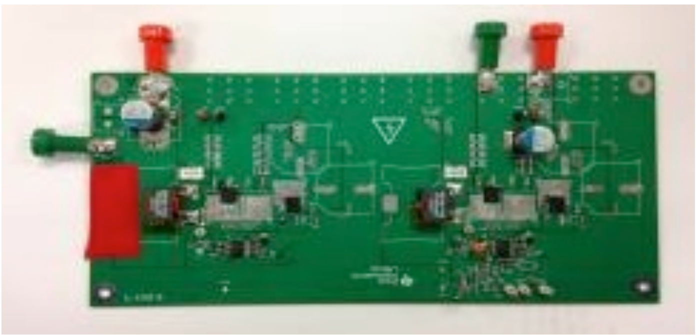


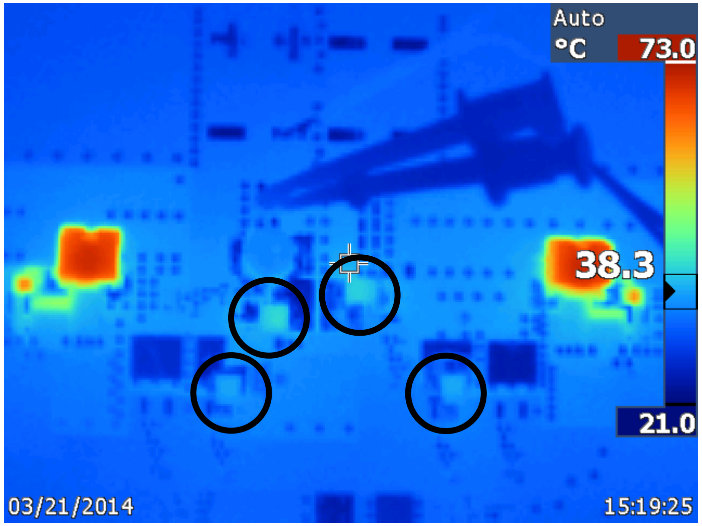


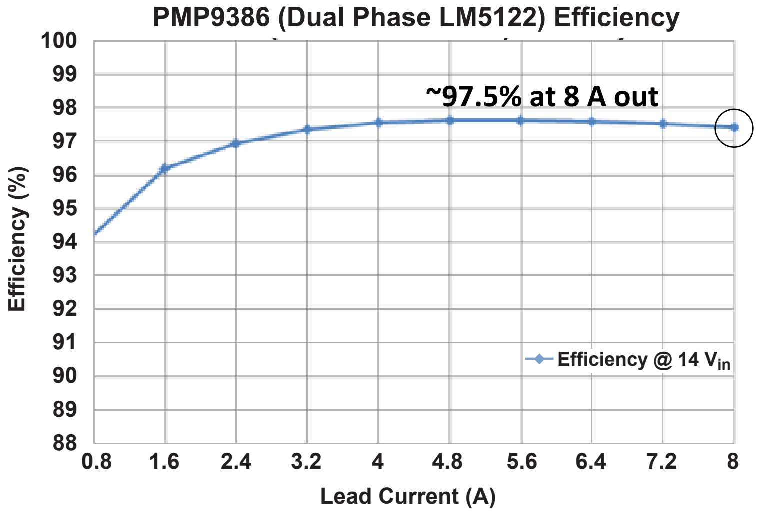
F_C ~15 kHz; PM ~50°

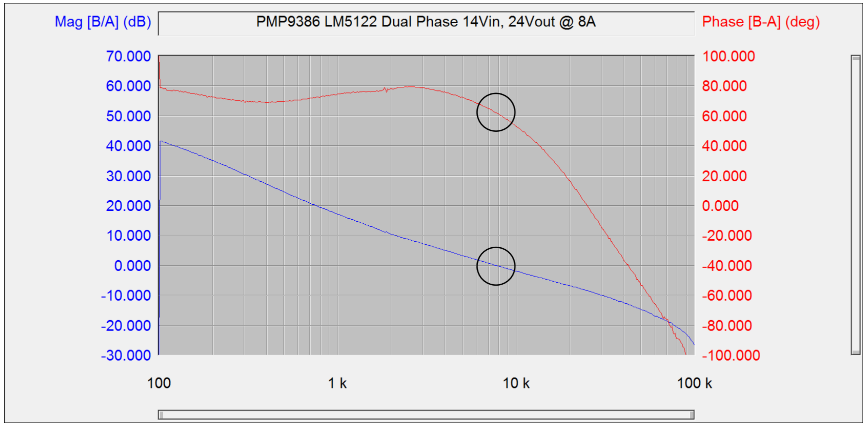
Bench Test Results: Dual Phase (PMP9386)

Efficiency and Thermals Comparison









F_C ~7.5 kHz, PM ~60°

Conclusion

- Using equations and step-by-step approach provided herein enables designer to adjust design for optimizing efficiency or size
- Both size, cost and performance can be modified by using multiphase boost approach
- Thermal performance improved using two phase approach
  - Thermal stress on FETs significantly reduced with multiphase approach
- For single phase boost
  - Increasing switching frequency in an attempt to reduce size will result in exceeding FET thermal limits
- For two phase boost
  - Increasing switching frequency is feasible without thermal stress on FETs
  - Significant reduction in size can be further gained

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