



中国电源学会第二十三届学术年会

The 23rd China Power Supply Society Conference (CPSSC'2019)

2019年11月1日至4日

地点: 深圳



Navitas

Let's go **GaNFast**[™]

基于氮化镓IC的150W高效率 高功率密度适配器设计

150W PFC+LLC using GaNFast Power ICs

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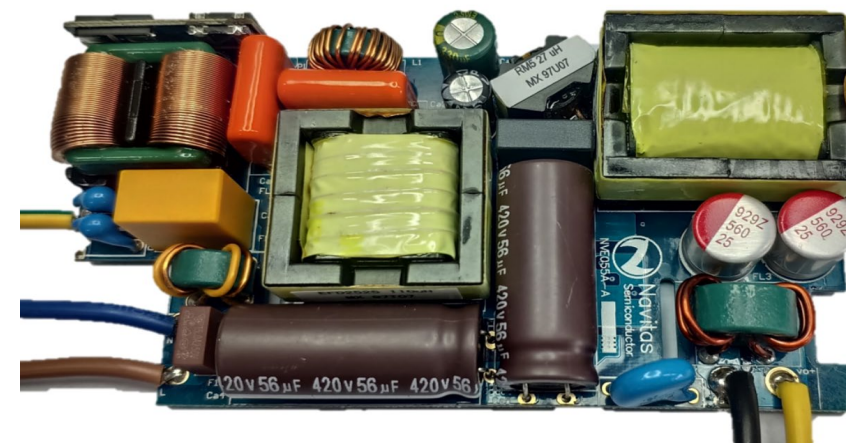
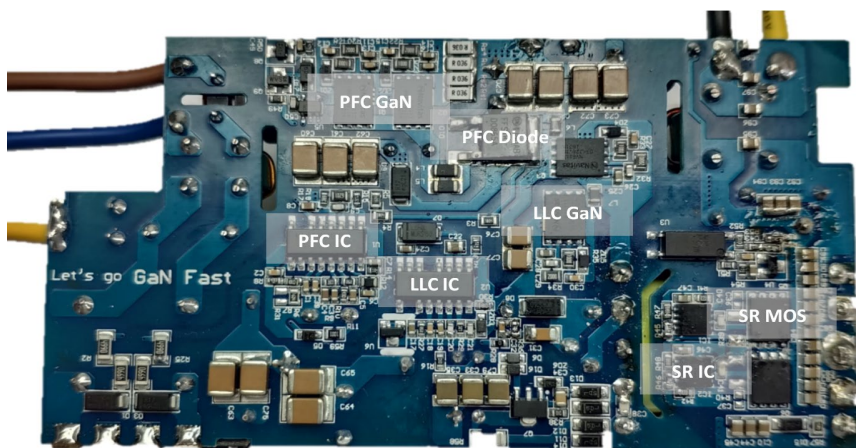
Agenda

- Appearance Review
- Test Result Review
- Key Waveform
- Controller Selection
- Layout notes
- GaN vs. Si (CoolMOS)



150W/19V adaptor

尺寸	Dimensions		103 x 55 x 17	mm
			96.3	cc
功率密度	Power Density	(uncased)	1.56	W/cc
			25.6	W/in ³
效率	Efficiency (full load)	230 V _{AC}	95.2	%
		115 V _{AC}	94.5	%
	Efficiency (4-pt. ave.)	230 V _{AC}	95.5	%
		115 V _{AC}	93.9	%





40% Size Reduction

HP 65W Adaptor



HP 65W Adaptor



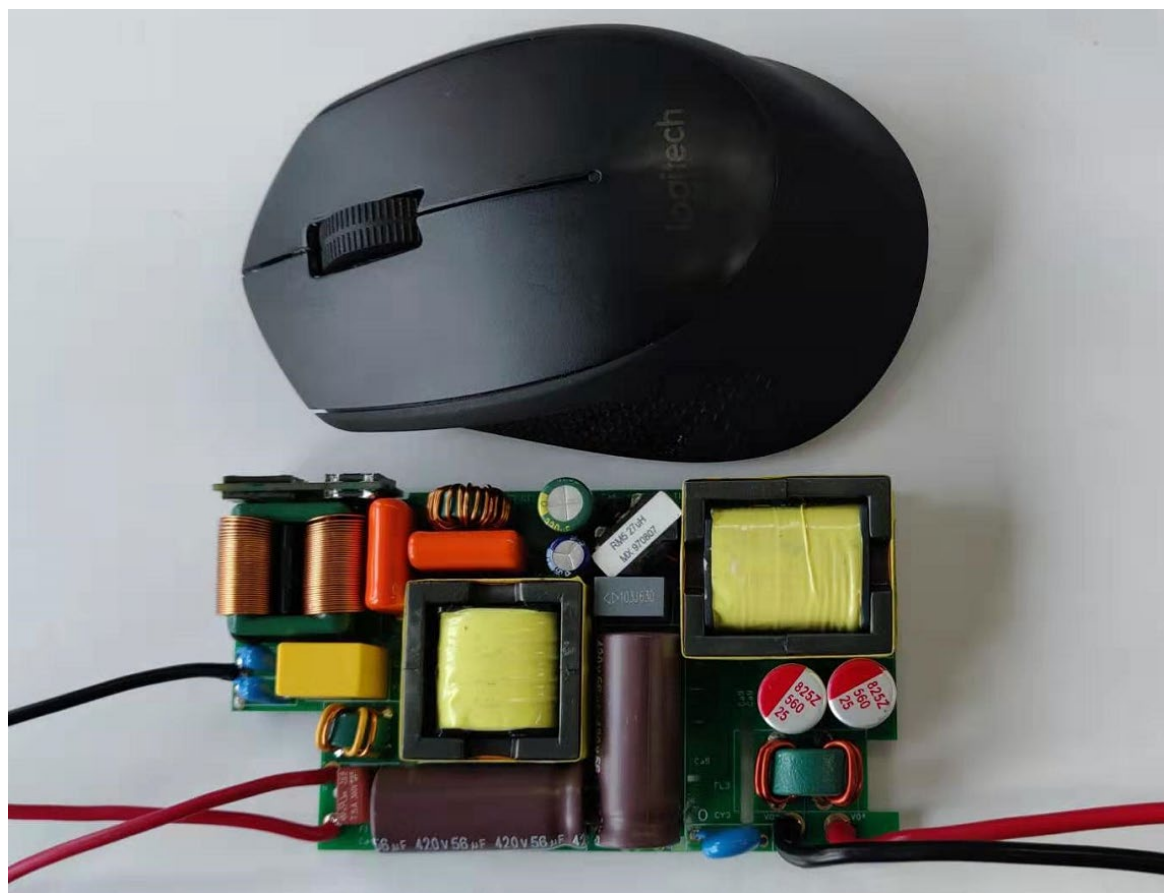


High Power-Density PCBA (96 cc)= 103 x 55 x 17mm



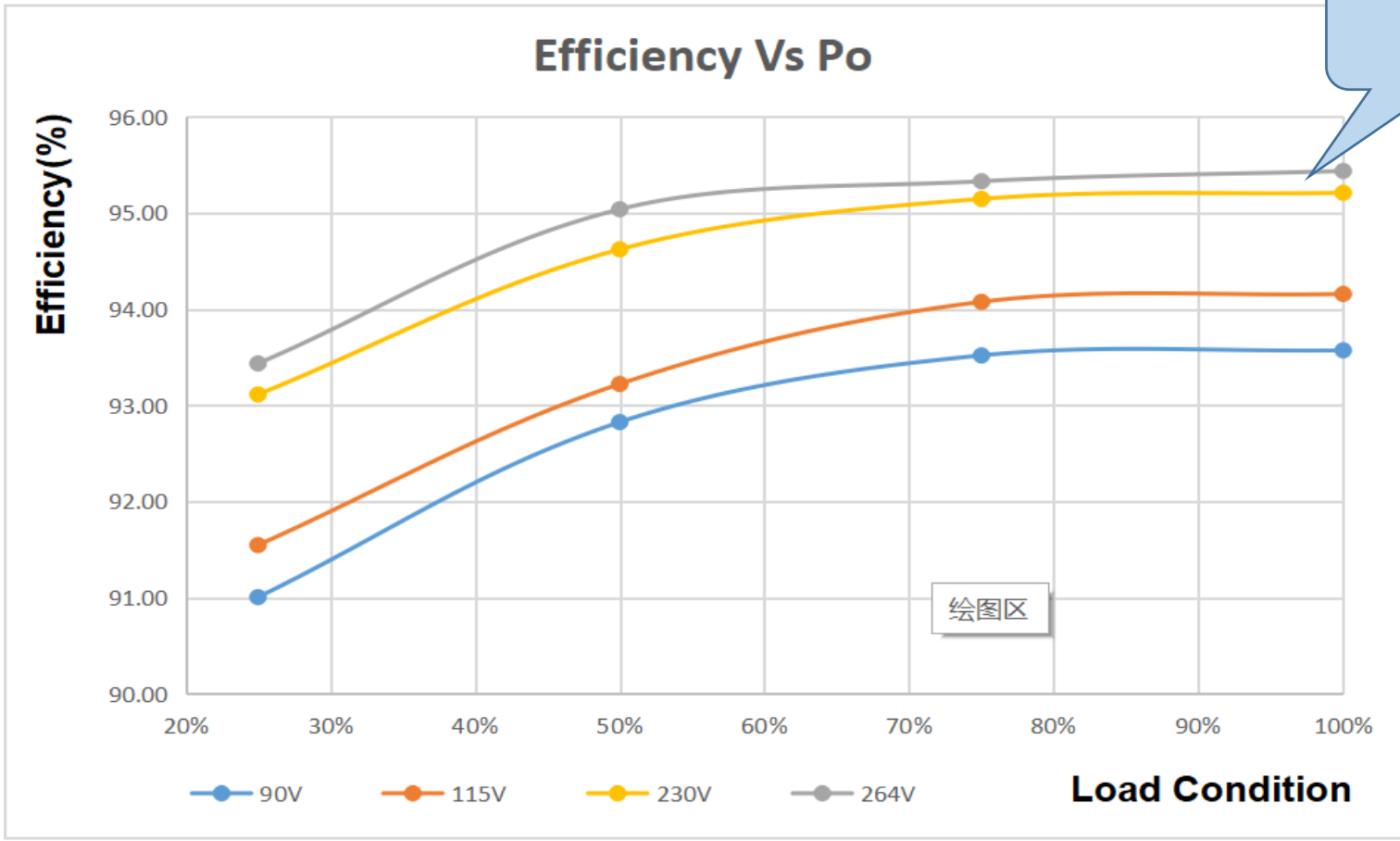
小米8

HP mouse





High Efficiency >93.5% @ 90 V_{AC}, Full Load



150W Thermal

- Test condition: Ambient Temp: 30 degree C ;
- full load $I_o=7.8A$

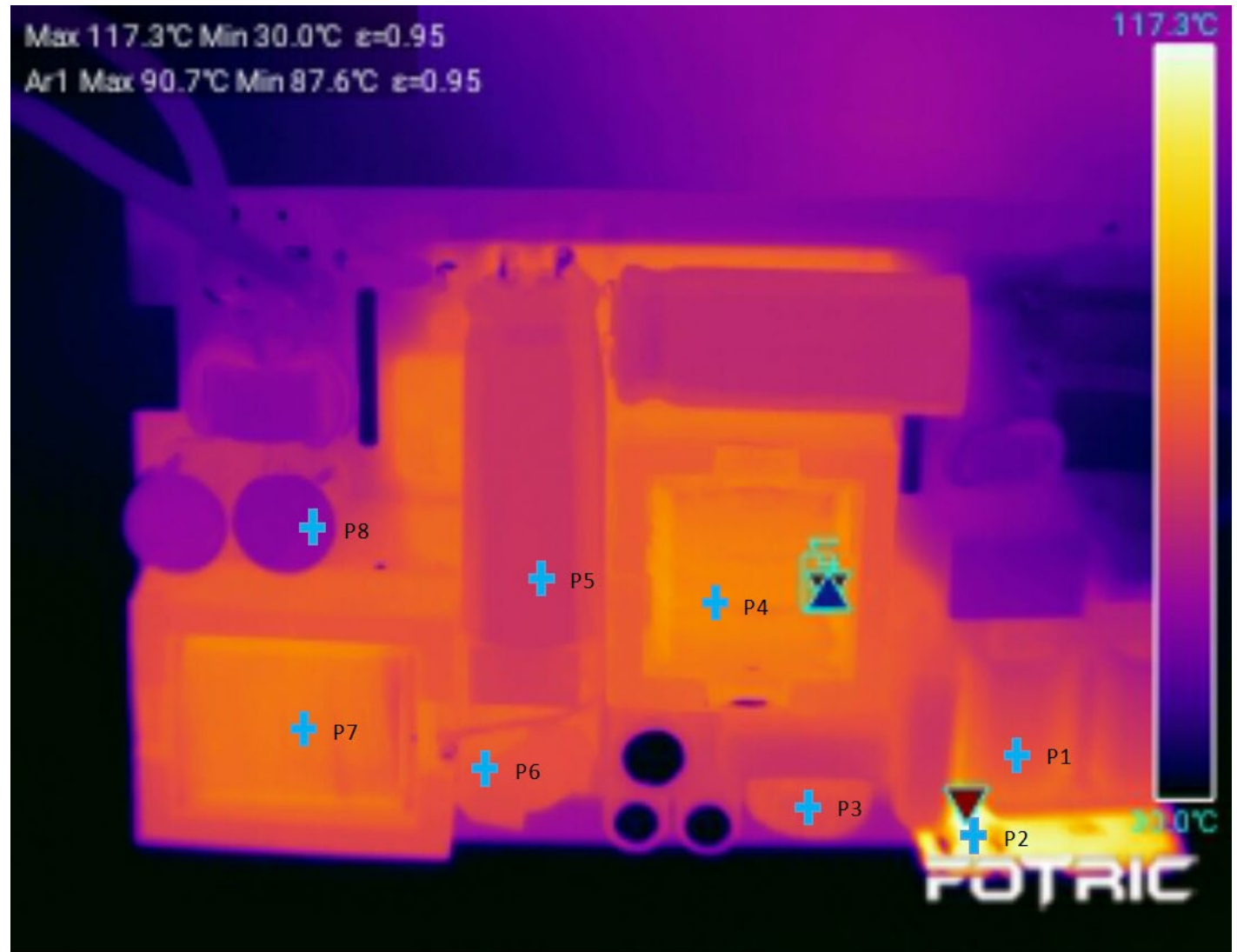
P1:	PFC IC	——	80°C
P2:	LLC IC	——	82°C
P3:	PFC GaN	——	84°C
P4:	PFC CS	——	84°C
P5:	PFC Diode	——	86°C
P6:	LLC GaN	——	85°C
P7:	SR IC	——	85°C
P8:	SR MOS	——	90°C



150W Thermal

- Test condition: Ambient Temp: 30 degree C ;
- full load $I_o=7.8A$

P1:	CMC	—82°C
P2:	Bridge	—117°C
P3:	DMC	—78°C
P4:	Inductor	—92°C
P5:	BUS E-CAP	—76°C
P6:	Resonant Inductor	—79°C
P7:	Transformer	—88°C
P8:	Secondary E-CAP	—65°C

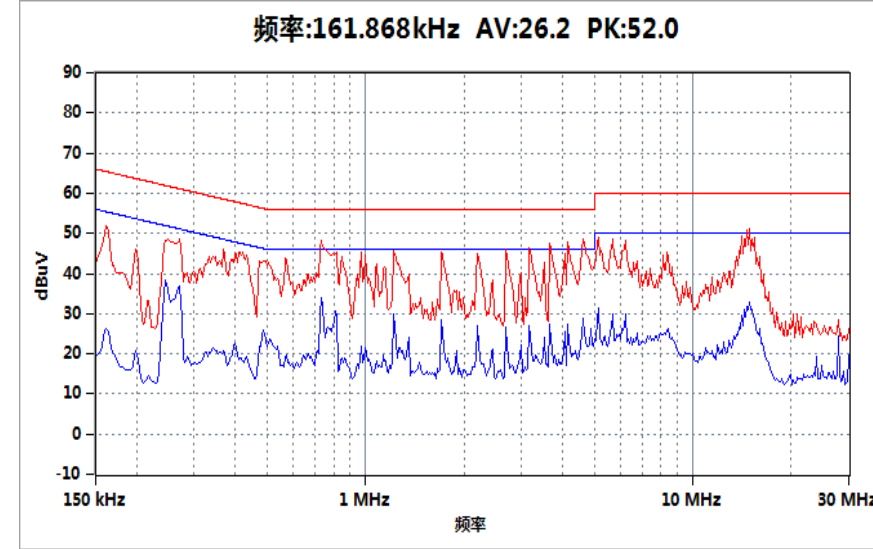
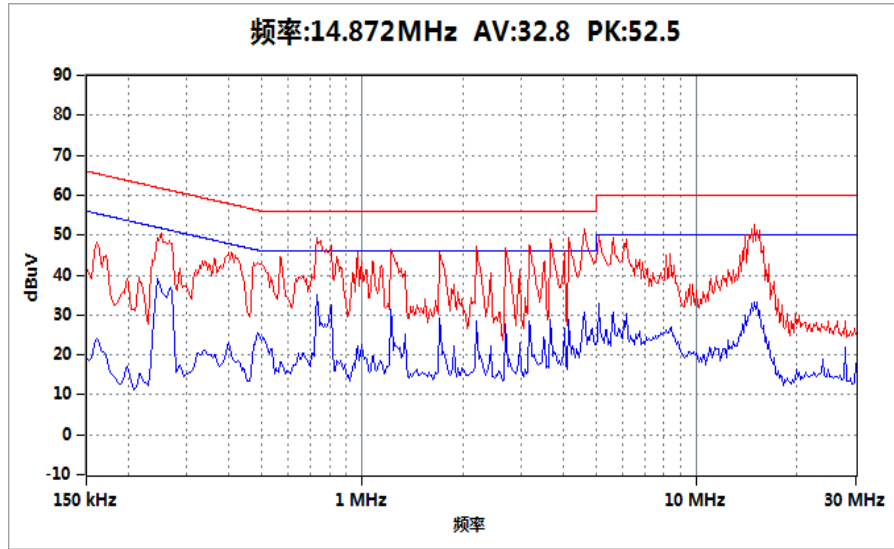


- Test condition: Ambient Temp: 30 degree C ;
- full load $I_o=7.8A$

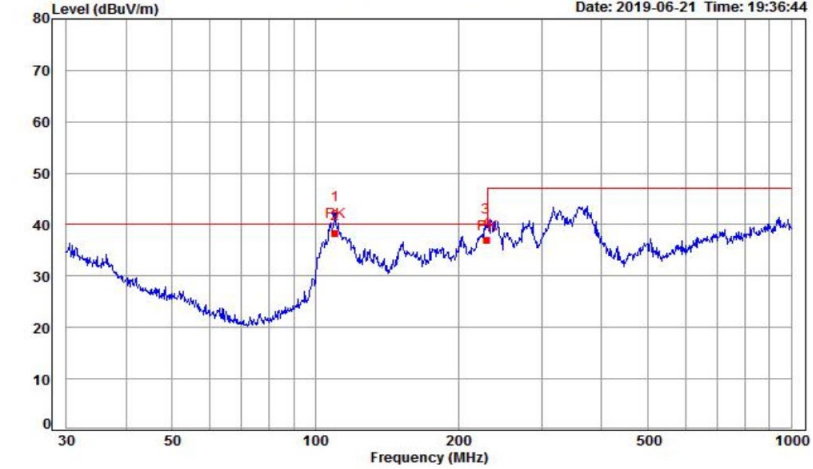
Test Conditions	Bridge	PFC GAN	LLC GAN	PFC diode	Inductor	Transformer	Resonant Inductor	BUS E-CAP	Secondray E-CAP	SR MOS
Vin=90Vac	117	84	85	86	92	88	79	76	65	90



150W EMC

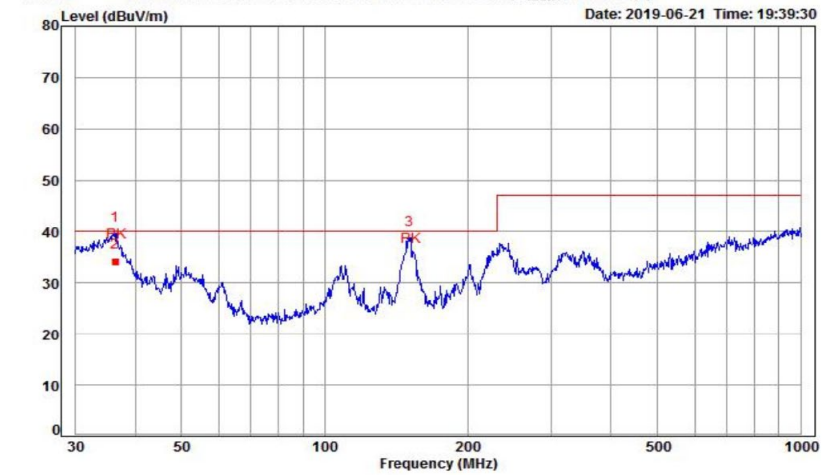


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Condition :
EUT : 150W-pinbi-115V-H
Power : AC 115V/50Hz
Env. : 23.5°C , 49%RH , 100.2KPa

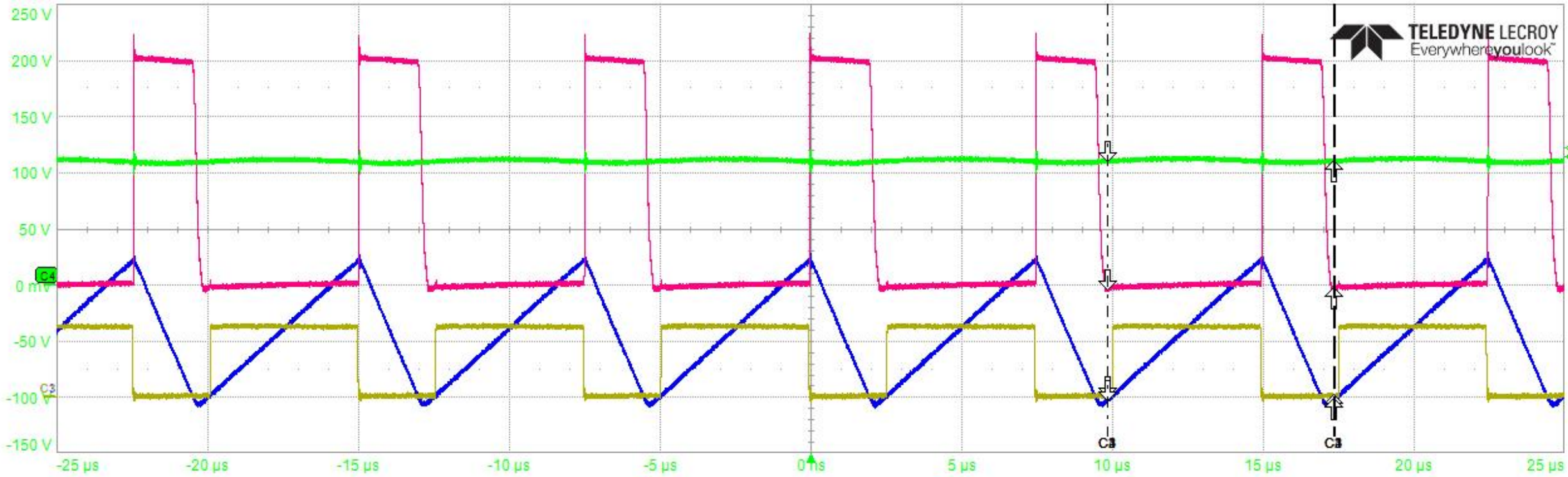
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Condition :
EUT : 150W-pinbi-115V-V
Power : AC 115V/50Hz
Env. : 23.5°C , 49%RH , 100.2KPa



Key Waveform, PFC

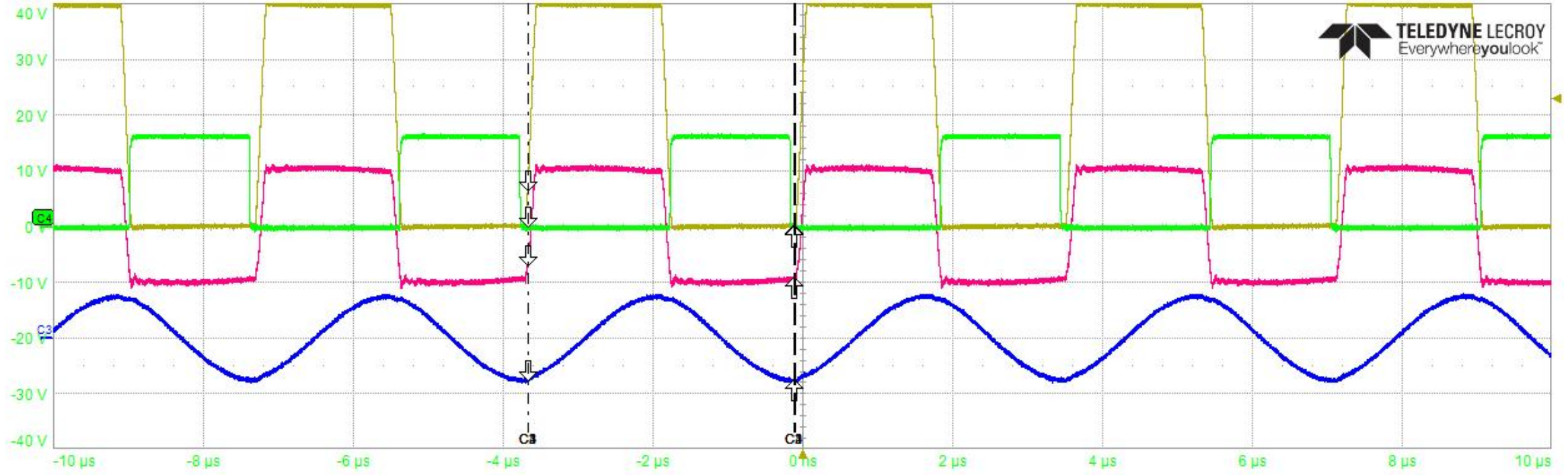


Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	13.1 V	5.13 A	10.01 V	122 V	133.35732 kHz	133.51023 kHz		
status	✓	✓	✓	✓	⚠	⚠		

C1	BwL	DC1M	C2	BwL	DC1M	C3	BwL	DC1M	C4	BwL	DC1M
10.0 V/div			100 V/div			2.00 A/div			50.0 V/div		
-30.00 V			-100.0 V			-6.000 A			-50.0 V ofst		
↓ 100 mV			↓ -7.1 V			↓ -110 mA			↓ 110.4 V		
↑ 190 mV			↑ -7.8 V			↑ -98 mA			↑ 109.6 V		
Δy 90 mV			Δy -700 mV			Δy 12 mA			Δy -800 mV		

Timebase	0.0 μs	Trigger	C4 DC
	5.00 μs/div	Stop	122.0 V
	500 kS	10 GS/s	Edge Positive
X1=	9.8629 μs	ΔX=	7.4710 μs
X2=	17.3339 μs	1/ΔX=	133.851 kHz

1: PFC DRIVER 2: PFC MOS VDS 3: PFC IL 4: VOLTAGE AFTER BRIDGE



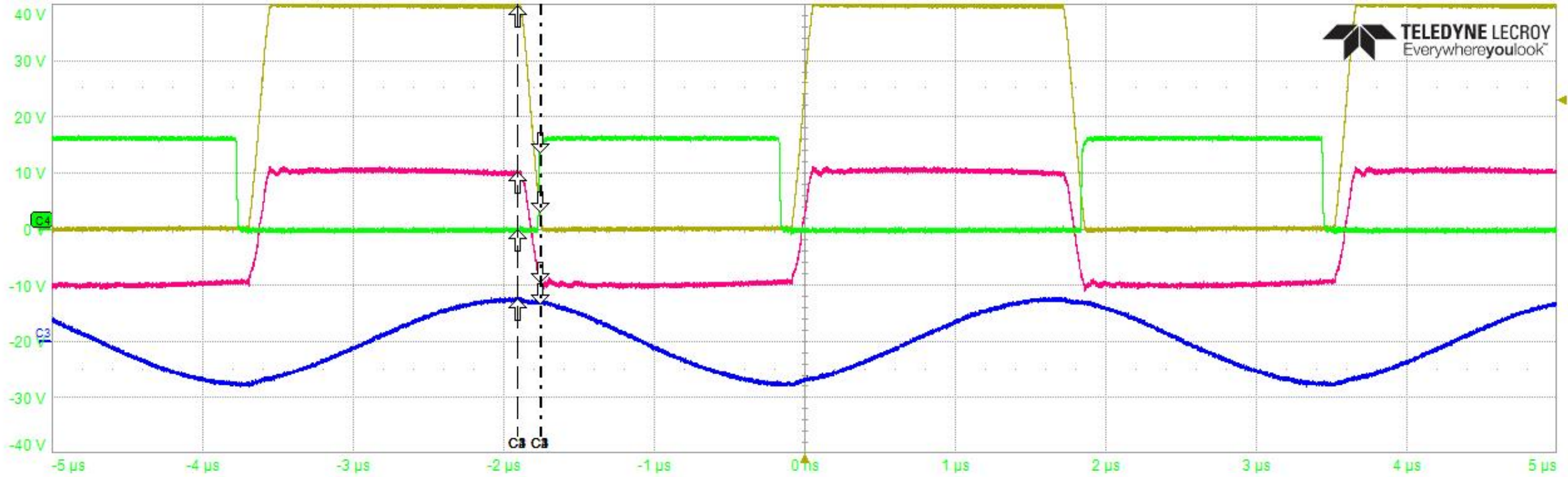
TELEDYNE LECROY
Everywhere you look™

Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	404 V	782 mA	277.2 V	16.6 V	277.22714 kHz	277.73212 kHz		
status	✓	✓	✓	✓	✓	✓		

C1	BwL	DC1M	C2	DC1M	C3	BwL	DC1M	C4	BwL	DC1M
100 V/div			200 V/div		1.00 A/div			10.0 V/div		
0.0 V offset			0.0 V offset		-2.000 A			0.00 V ofst		
64.2 V			-139.3 V		-756 mA			50 mV		
200 mV			-188.3 V		-774 mA			-330 mV		
Δy			-63.9 V		-18 mA			-380 mV		

Tbase	0.00 µs	Trigger	C1	DC
	2.00 µs/div	Stop		230 V
	200 kS	10 GS/s	Edge	Positive
X1=	-3.6655 µs	ΔX=	3.5624 µs	
X2=	-103.1 ns	1/ΔX=	280.710 kHz	

1: LLC SW 2: VTP 3: IR 4: DRIVER



TELEDYNE LECROY
Everywhere you look™

Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	404 V	774 mA	278.1 V	16.5 V	277.27550 kHz	276.90159 kHz		
status	✓	✓	✓	✓	✓	✓		

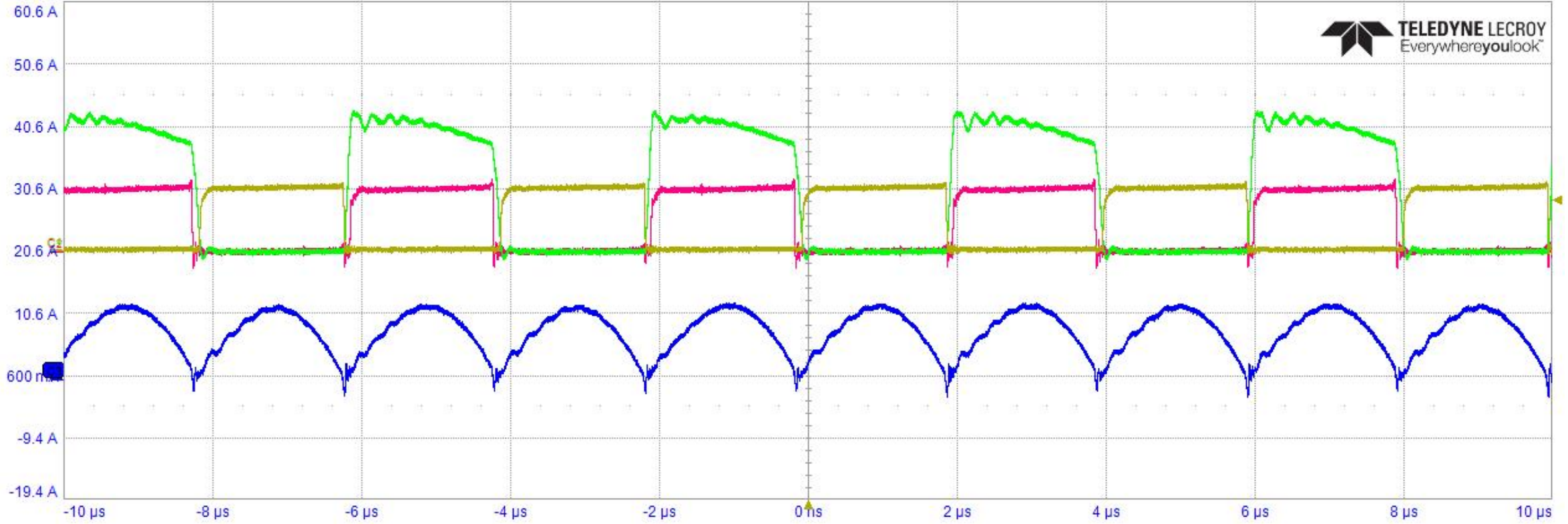
C1	BwL	DC1M	C2	DC1M	C3	BwL	DC1M	C4	BwL	DC1M
100 V/div			200 V/div		1.00 A/div			10.0 V/div		
0.0 V offset			0.0 V offset		-2.000 A			0.00 V ofst		
↓ 31.7 V			↓ -187.5 V		↓ 681 mA			↓ 13.72 V		
↑ 393.5 V			↑ 196.6 V		↑ 726 mA			↑ -470 mV		
Δy 361.9 V			Δy 384.1 V		Δy 44 mA			Δy -14.19 V		

Tbase	0.00 μs	Trigger	<input checked="" type="checkbox"/> <input type="checkbox"/>
	1.00 μs/div	Stop	230 V
	100 kS	Edge	Positive
X1=	-1.7568 μs	ΔX=	-151.4 ns
X2=	-1.9082 μs	1/ΔX=	-6.605 MHz

1: LLC SW 2: VTP 3: IR 4: DRIVER



Key Waveform, SR



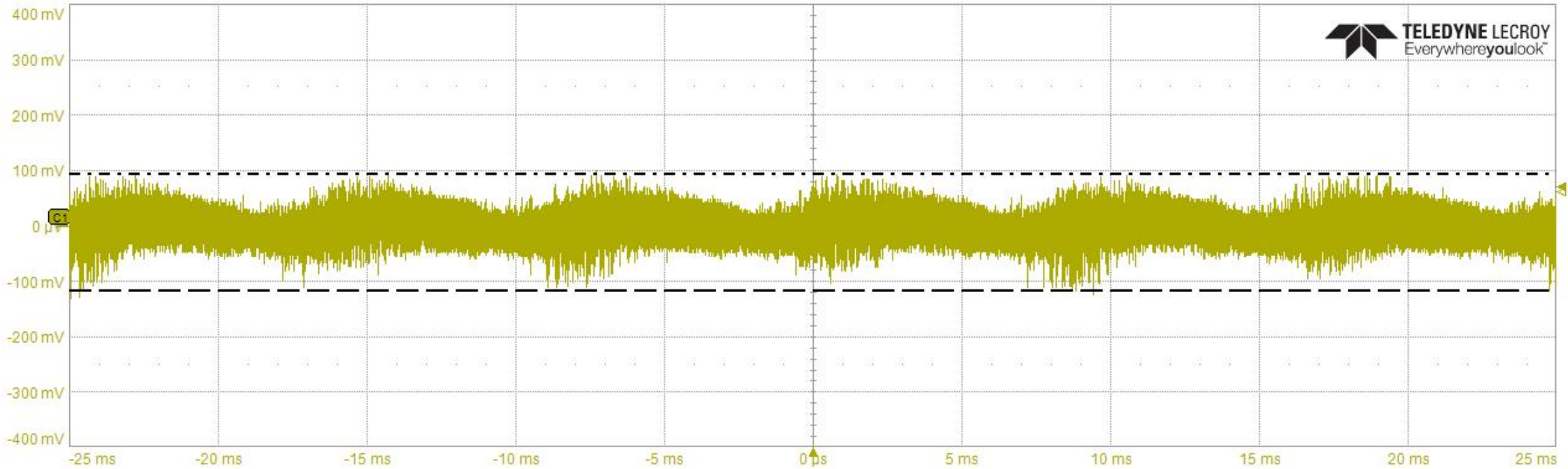
Measure	P1: max(C1)	P2: max(C3)	P3: rms(C1)	P4: max(C4)	P5: freq(C1)	P6: freq(C3)	P7: max(C3)	P8: rms(C3)
value	5.5 V	12.2 A	3.47 V	44.9 V	247.63497 kHz	488.8723 kHz		
status	✓	✓	✓	✓	✓	✓		

C1	BwL	DC1M	C2	DC1M	C3	BwL	DC1M	C4	BwL	DC1M
5.00 V/div			5.00 V/div		10.0 A/div			20.0 V/div		
0.00 V ofst			-100 mV		-20.60 A			0.00 V ofst		

Tbase	0.00 μs	Trigger	<input checked="" type="checkbox"/> C1	<input type="checkbox"/> DC
	2.00 μs/div	Stop	4.05 V	
	200 kS	10 GS/s	Edge	Positive

1: H-DRIVER 2: LOW-DRIVER 3: I 4: VDS

Key Waveform, Ripple



Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	100 mV	74 mA	12.1 mV	7 V	266.706 kHz	--		
status	✓	✓	✓	✓	⌵	⌵		

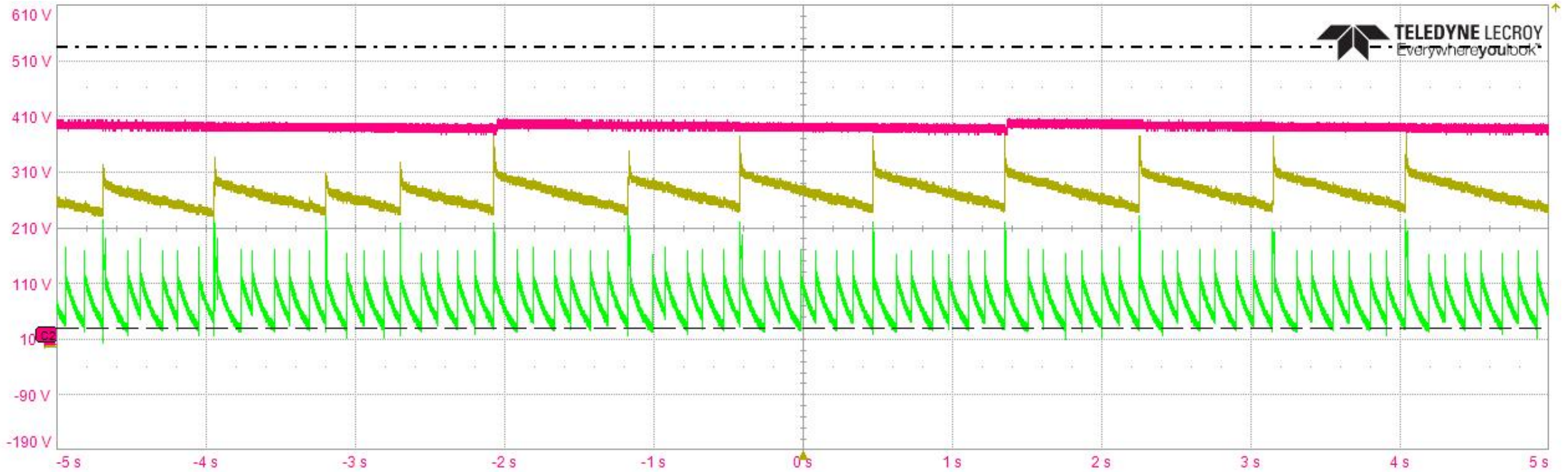
C1	BwL	AC1M
100 mV/div		
0.0 mV ofst		
---- 93 mV		
----- -116 mV		
Δy -209 mV		

Tbase	0.0 ms	Trigger	C1	⏹
	5.00 ms/div	Stop	63 mV	
	2.5 MS	50 MS/s	Edge	Positive

1: VO



Key Waveform, Standby



Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	19.3 V	2.40 A	13.71 V	233 V	1.12310853 Hz	7.723813 Hz		
status	✓	✓	✓	✓	.r.	.r.		

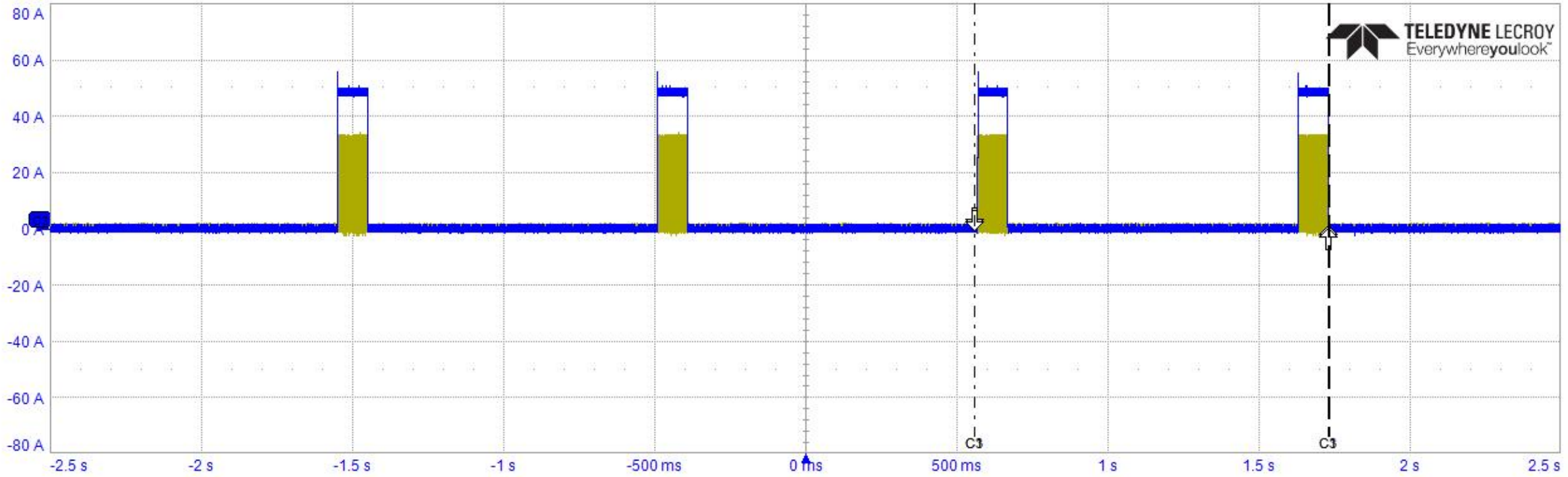
C1	BwL	DC1M	C2	DC1M	C4	BwL	DC1M
5.00 V/div			100 V/div		100 V/div		
-10.65 V			-210.0 V		-210.0 V		
---- 26.95 V			---- 536 V		---- 536 V		
..... 1.60 V		 29 V	 29 V		
Δy -25.35 V			Δy -507 V		Δy -507 V		

Timebase	0.00 s	Trigger	C1 DC
Roll	1.00 s/div	Stop	31.15 V
2.5 MS	250 kS/s	Edge	Positive

1: VCC 2: VBUS 3: VC



Key Waveform, SCP



Measure	P1:max(C1)	P2:max(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	16.9 V	55.8 A	2.83 V	12 V	169.742813023 kHz	944.10273 mHz		
status	✓	✓	✓	✓		✓		

Channel	Scale	Offset	Position	Delta
C1	10.0 V/div	0.00 V ofst	330 mV	0.00 V
C2	20.0 A/div	0.00 A ofst	-660 mA	0.00 A
C3	20.0 A/div	0.00 A ofst	-660 mA	0.00 A

Parameter	Value
Timebase	0.00 s
Roll	500 ms/div
2.5 MS	500 kS/s
Trigger	C4 DC
Stop	-3.0 V
Edge	Positive
X1=	560.760 ms
X2=	1.732138 s
ΔX=	1.171378 s
1/ΔX=	853.695 mHz

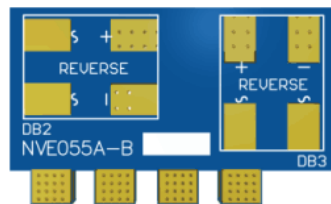
1: LLC DRIVER 2: IO



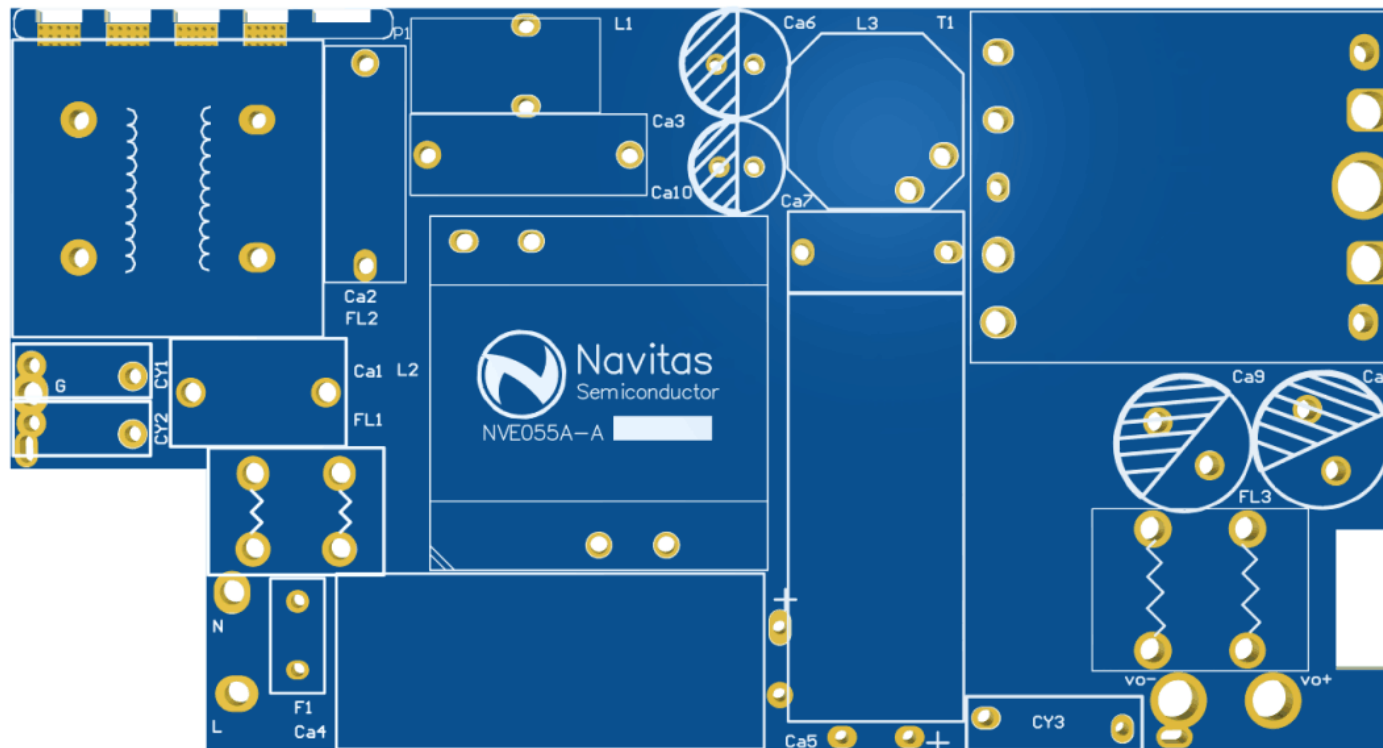
Easy-to-Build

- 2 PCBs

AC Bridge

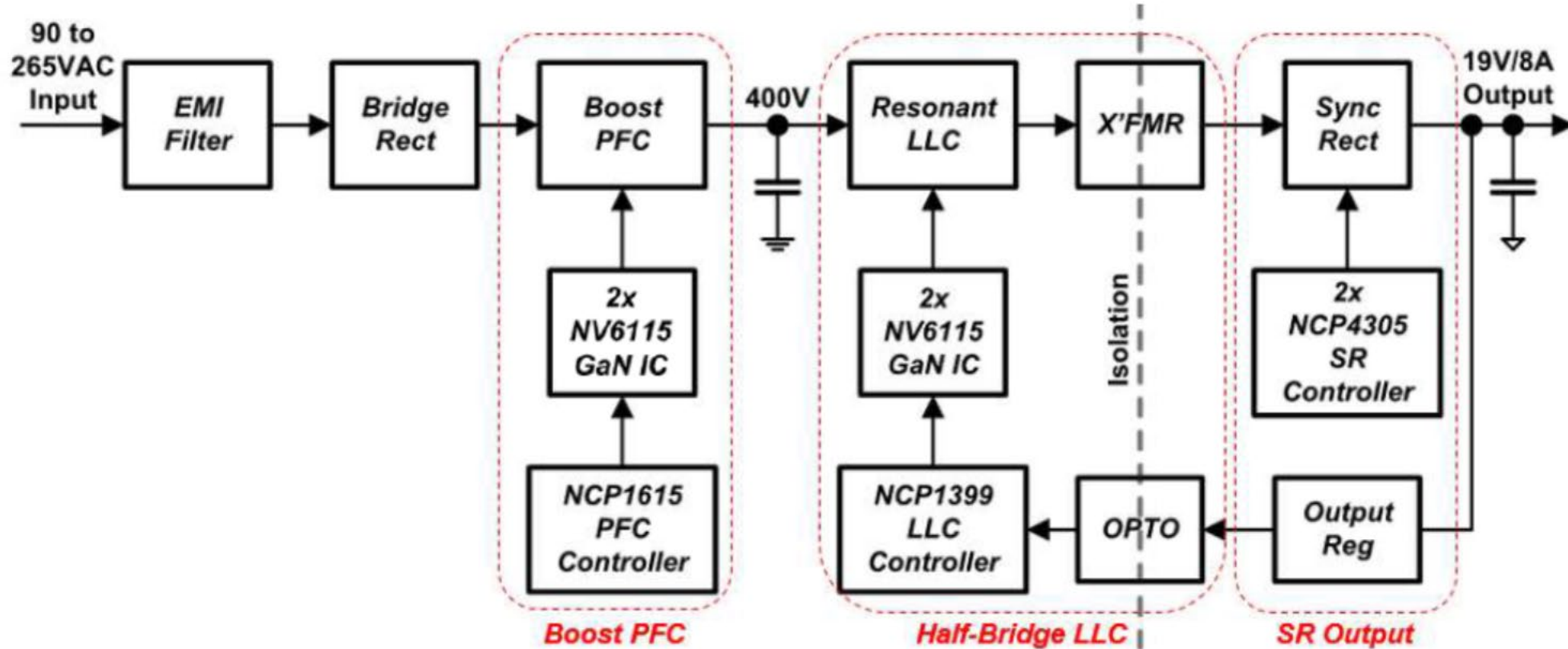


Main board



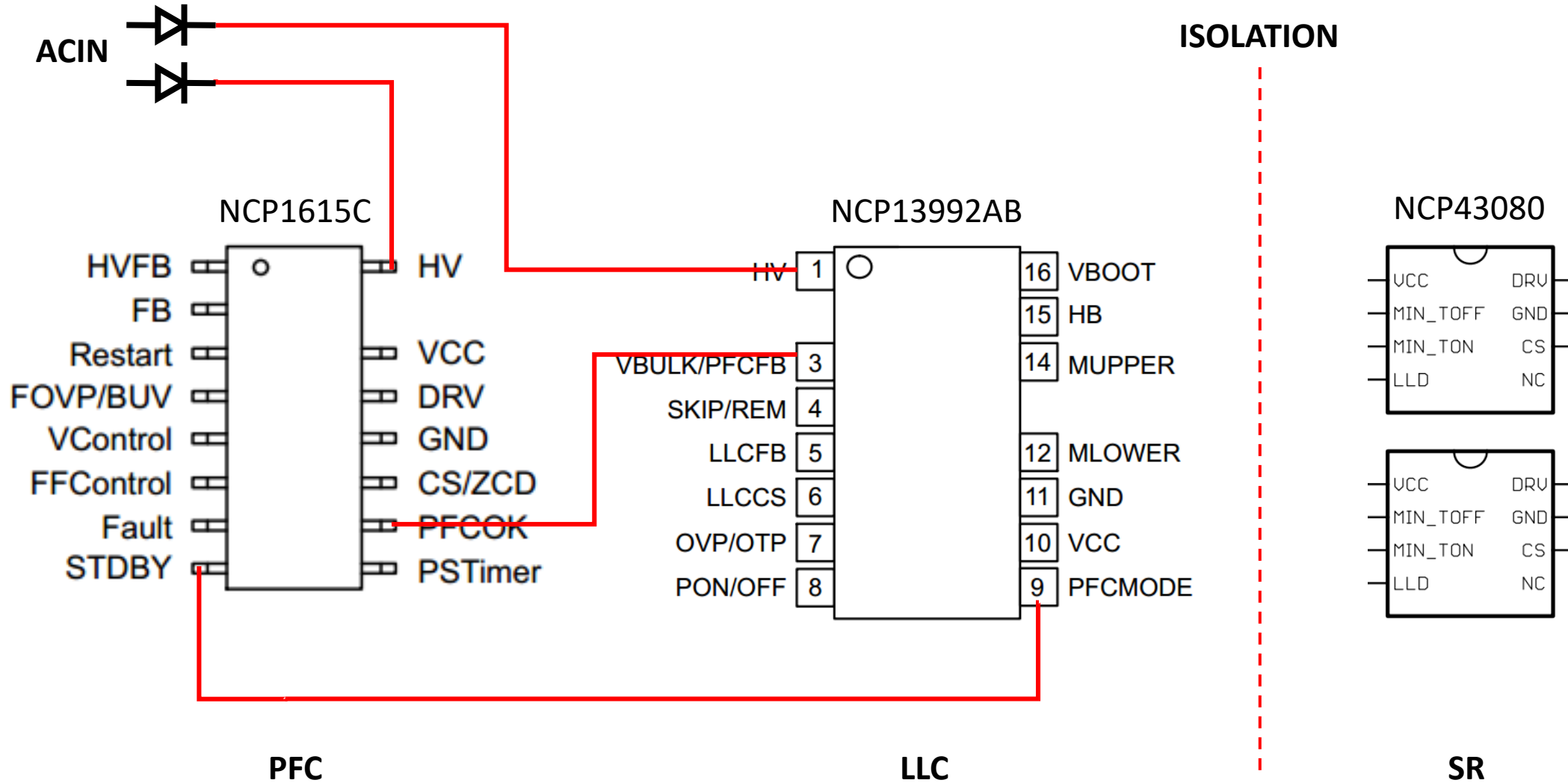


Schematic Architecture



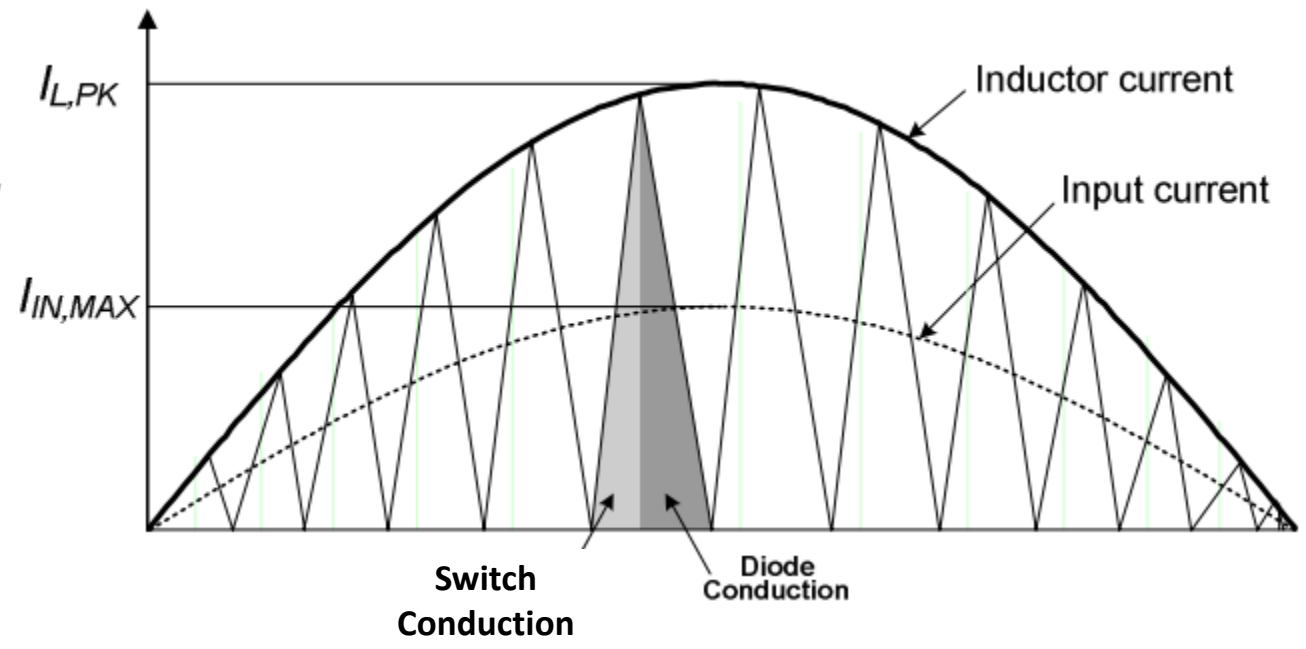
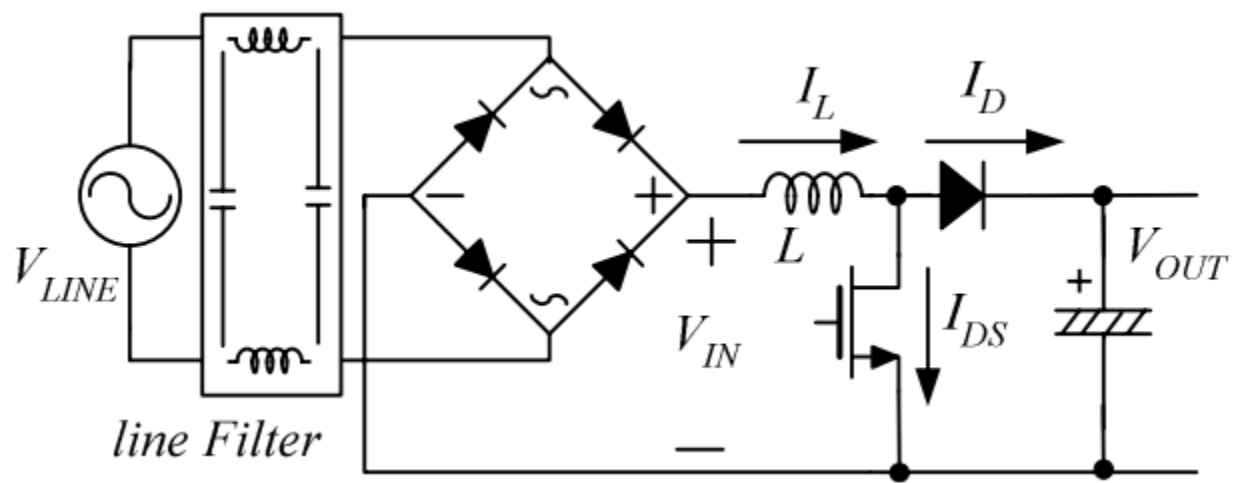


ON Semi PFC/LLC/SR Chip Set



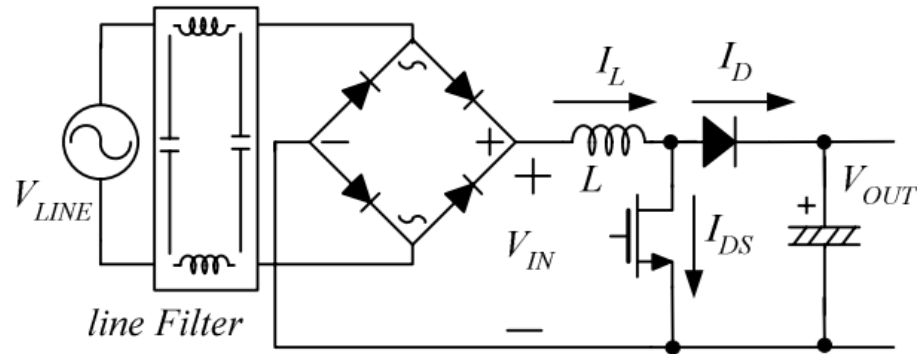


Boost PFC Circuit

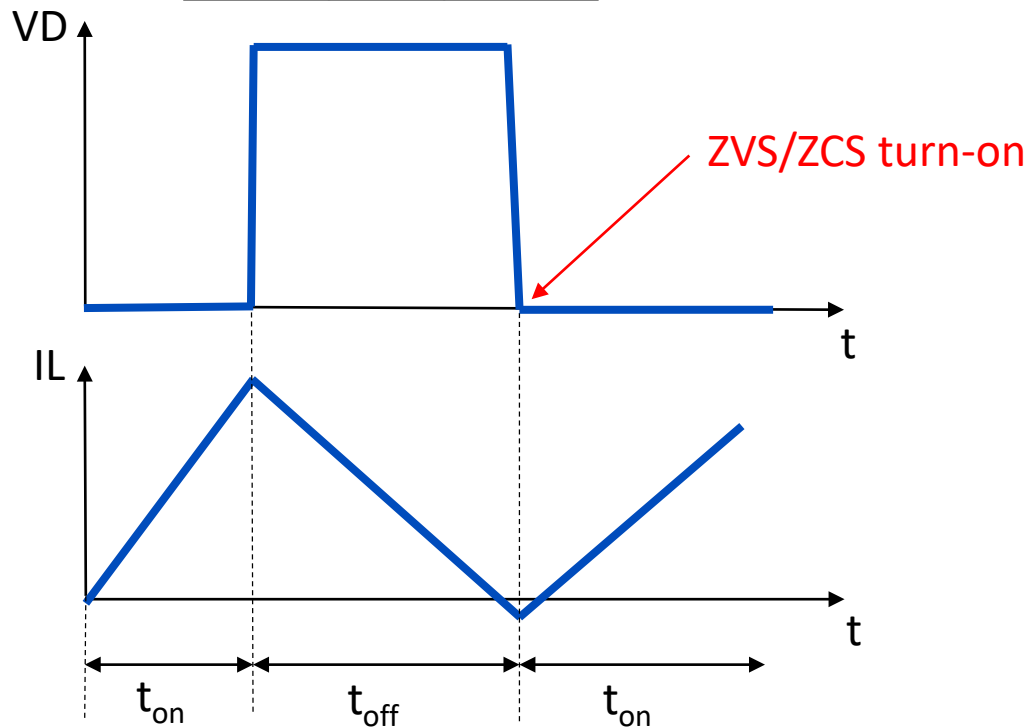




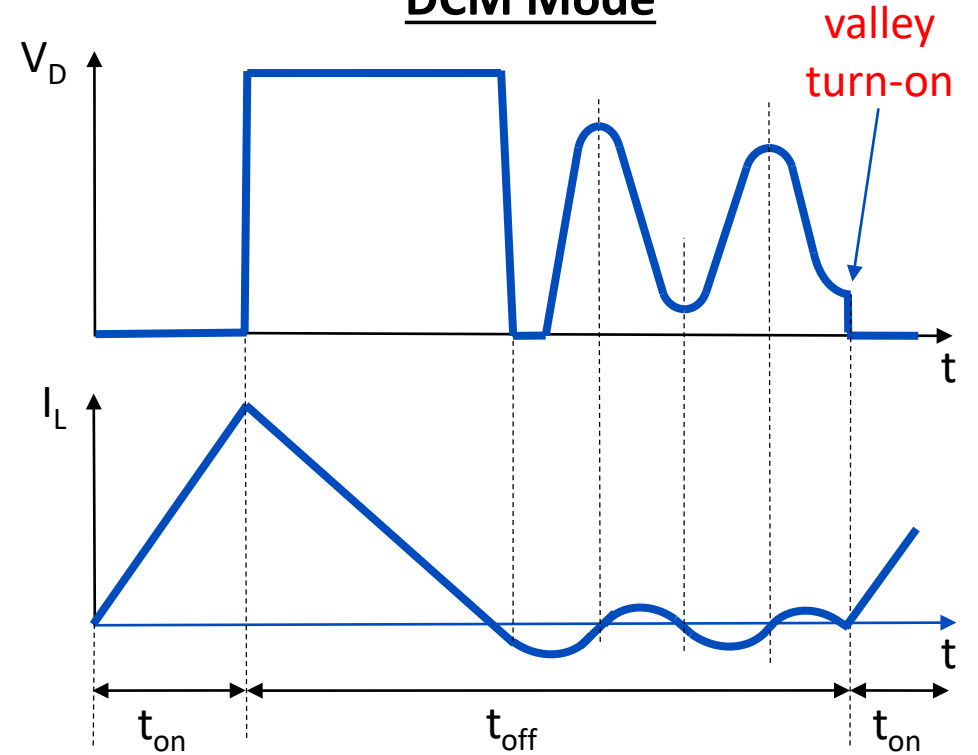
Boost PFC Circuit Modes



CrCM (BCM) Mode

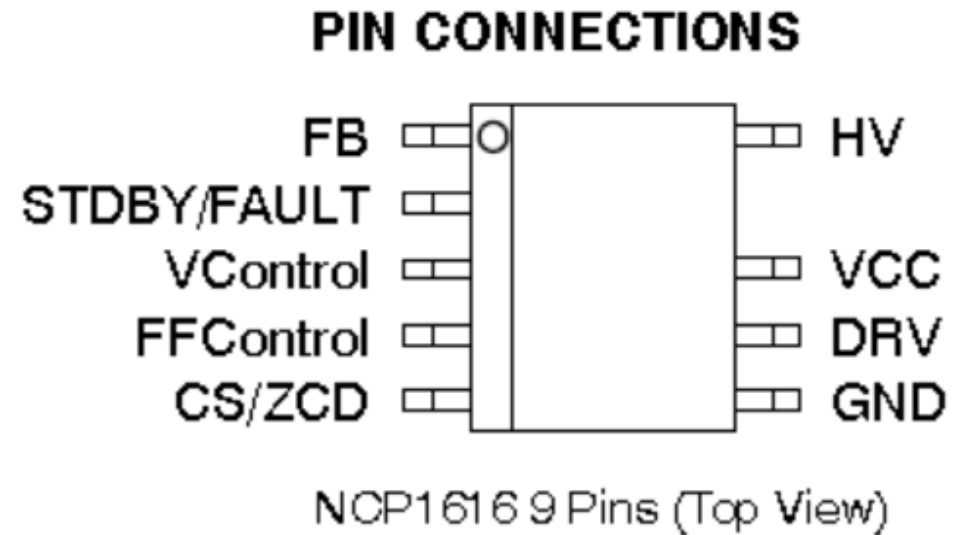
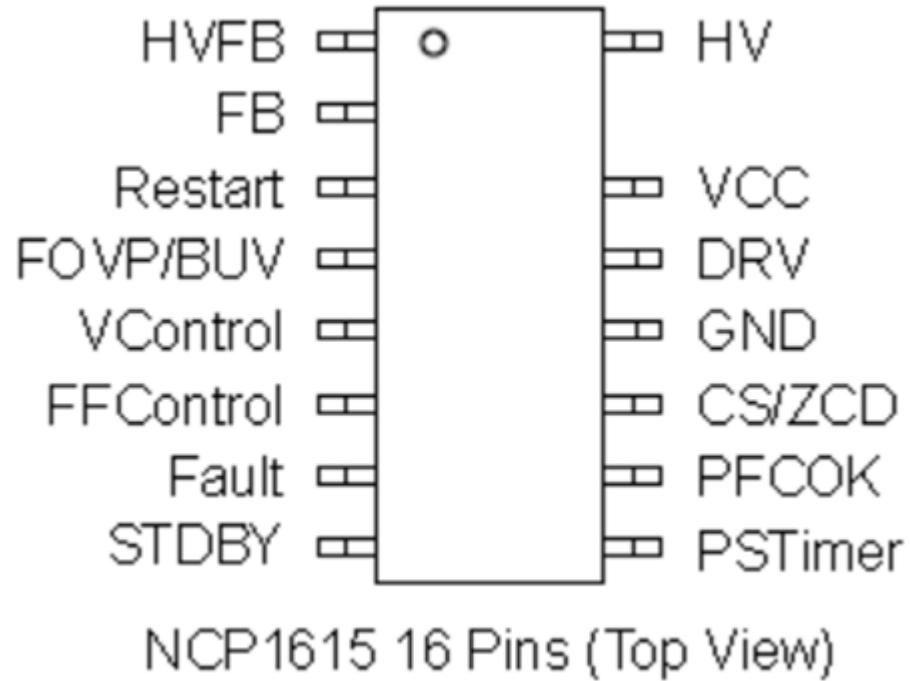


DCM Mode



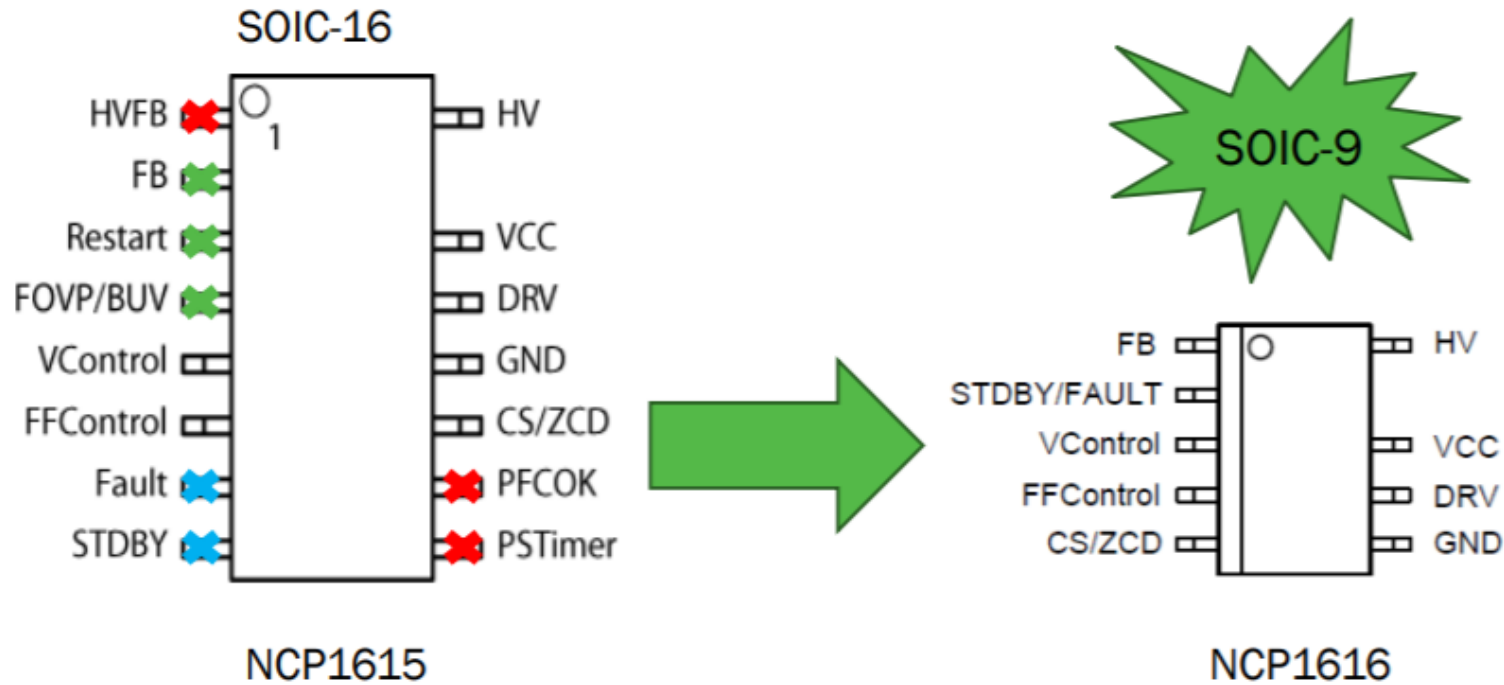


PFC: $F_{SW}(\text{MIN}) = 200 \text{ kHz}$





NCP1615 → NCP1616

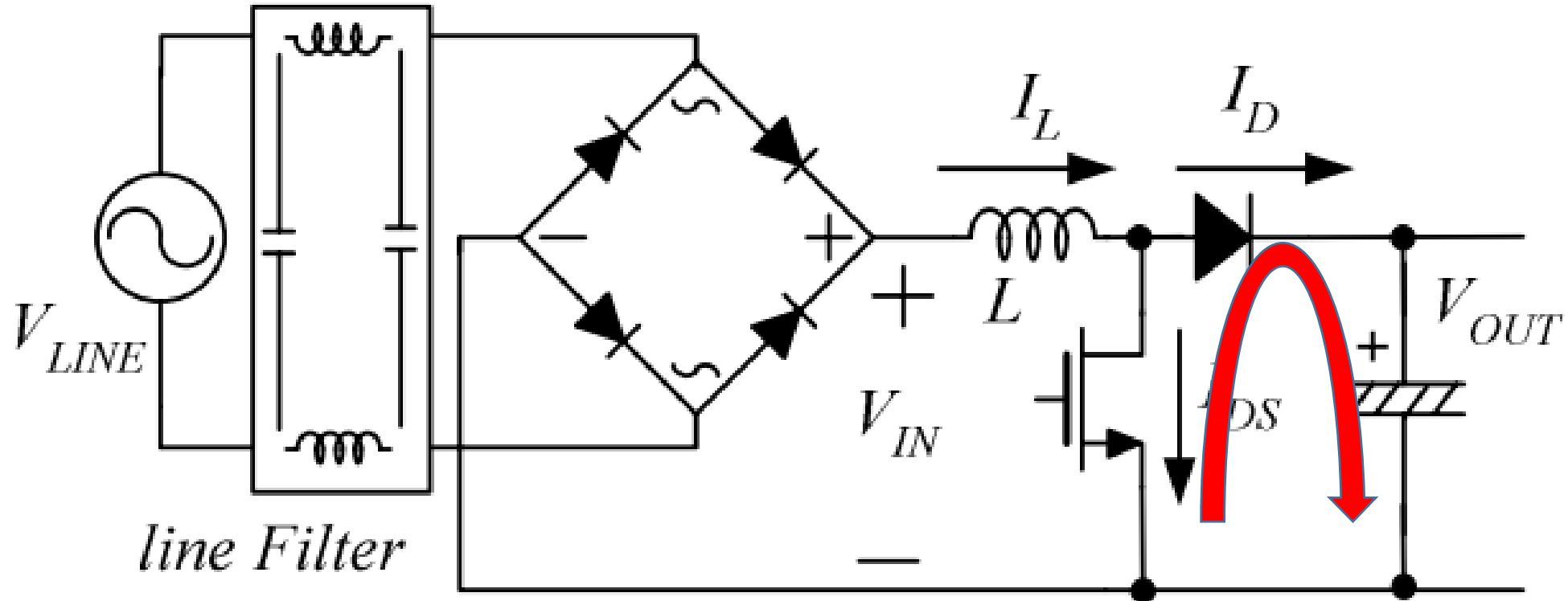


- ✖ Pins removed
- ✕ Pins combined
- ✕ Pins combined

- Current controlled frequency foldback (CCFF) scheme for high efficiency across line and load.
- Integrated high voltage start-up.



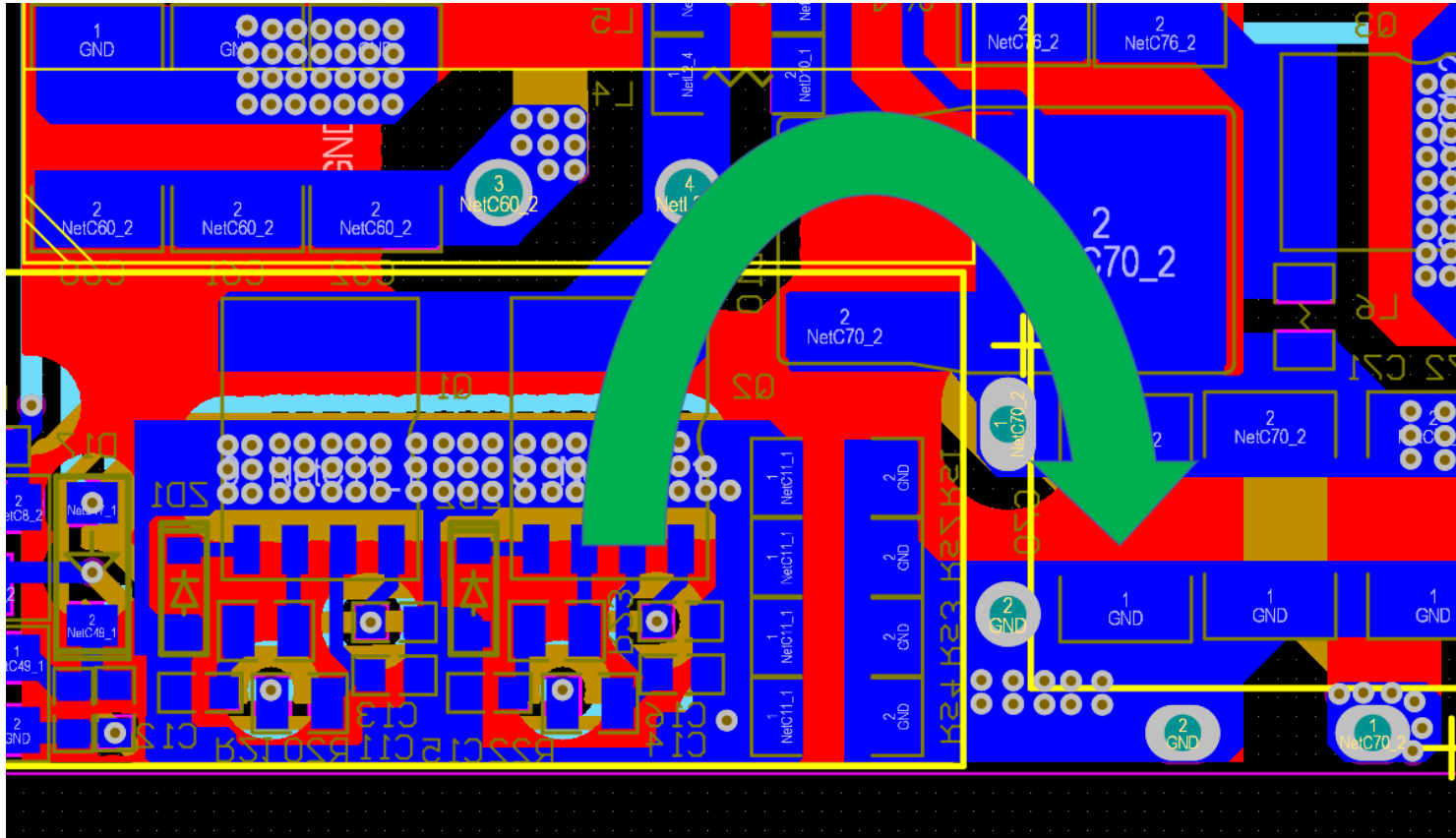
Layout Guideline



- When the FET is turned off, the current transferred into the diode instantly, which creates huge di/dt, so the loop must be minimized.



Layout Guideline

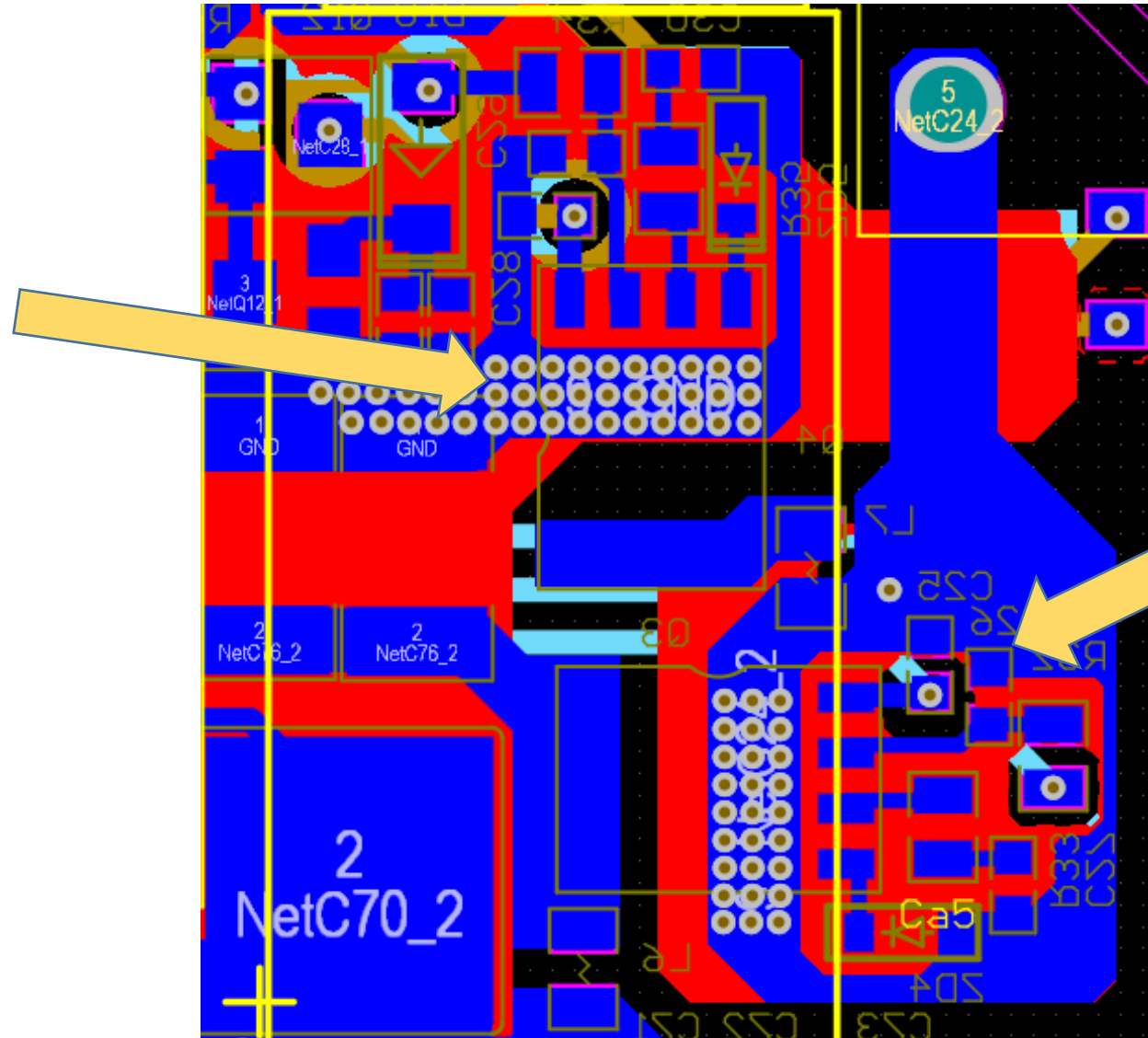


- When the FET is turned off, the current transferred into the diode instantly, which creates huge di/dt , so the loop must be minimized.



Layout Guideline

Low-side GaN



High-side GaN

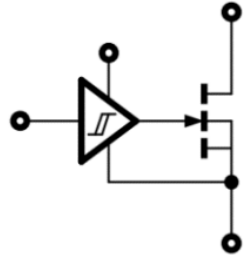
Should have no any overlap between high-side node and low-side node.



NV6115/7 (650V GaNFast™ Power IC) GaNFast™



QFN 5 x 6 mm



Simplified schematic

Features

- Monolithically-integrated gate drive
- Wide logic input range with hysteresis
- 5 V / 15 V input-compatible
- Wide V_{CC} range (10 to 24 V)
- Programmable turn-on dV/dt
- 200 V/ns dV/dt immunity
- 650 V eMode GaN FET
- Low 170 m Ω resistance
- Zero reverse recovery charge
- 2 MHz operation

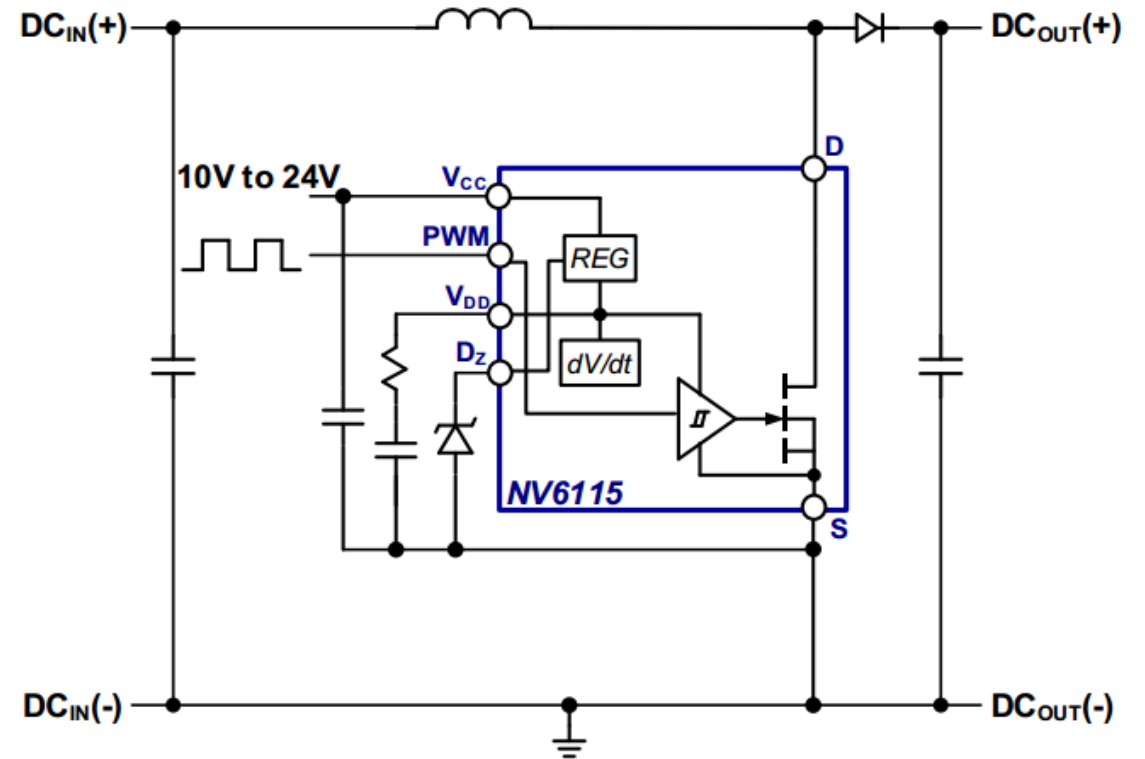


Fig 1. Boost application diagram



NV6115 (Connection, Components)

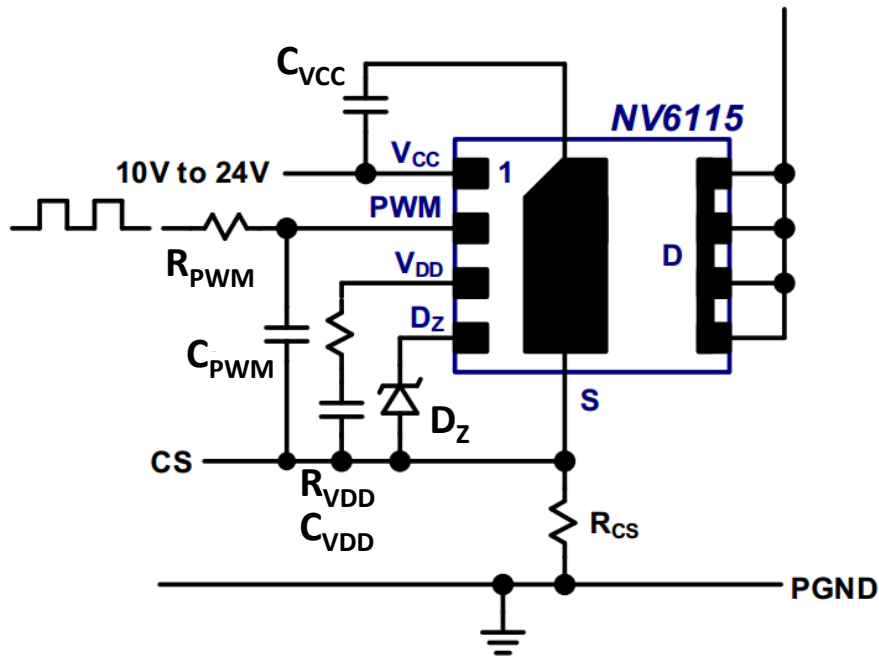


Fig 1. GaN Power IC connection diagram

SYM	DESCRIPTION	TYP	UNITS
C_{VCC}	V_{CC} supply filter capacitor	0.1	μF
C_{VDD}	V_{DD} supply capacitors	0.01	μF
R_{VDD}	Gate drive turn-on current set resistor	25 (range 10 to 400)	Ω
R_{PWM}	PWM filter resistor	100	Ω
C_{PWM}	PWM filter capacitor	100	pF

Table I. Recommended component values (typical only).

SYM	DESCRIPTION	PART NO.	SUPPLIER	TYP	UNITS
D_Z	V_{DD} set Zener diode (D_Z pin)	BZT52B6V2 RHG	Taiwan Semiconductor Corporation	6.2	V
		MM3Z6V2ST1G	ON-Semiconductor		
		PDZ6.2B.115	Nexperia (NXP)		
		PLVA662A.215	Nexperia (NXP)		
		LM3Z6V2T1	Leshan Radio Company		

Table II. Qualified Zener diode components to be used with this GaN Power IC.



NV6115 (Timing Diagram)

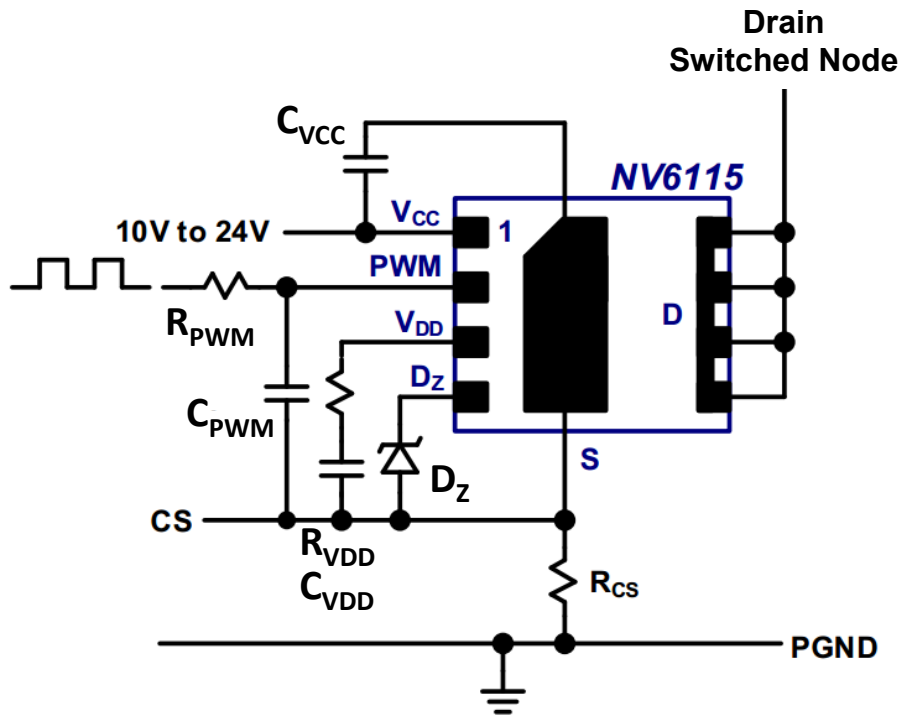


Fig 1. GaN Power IC connection diagram

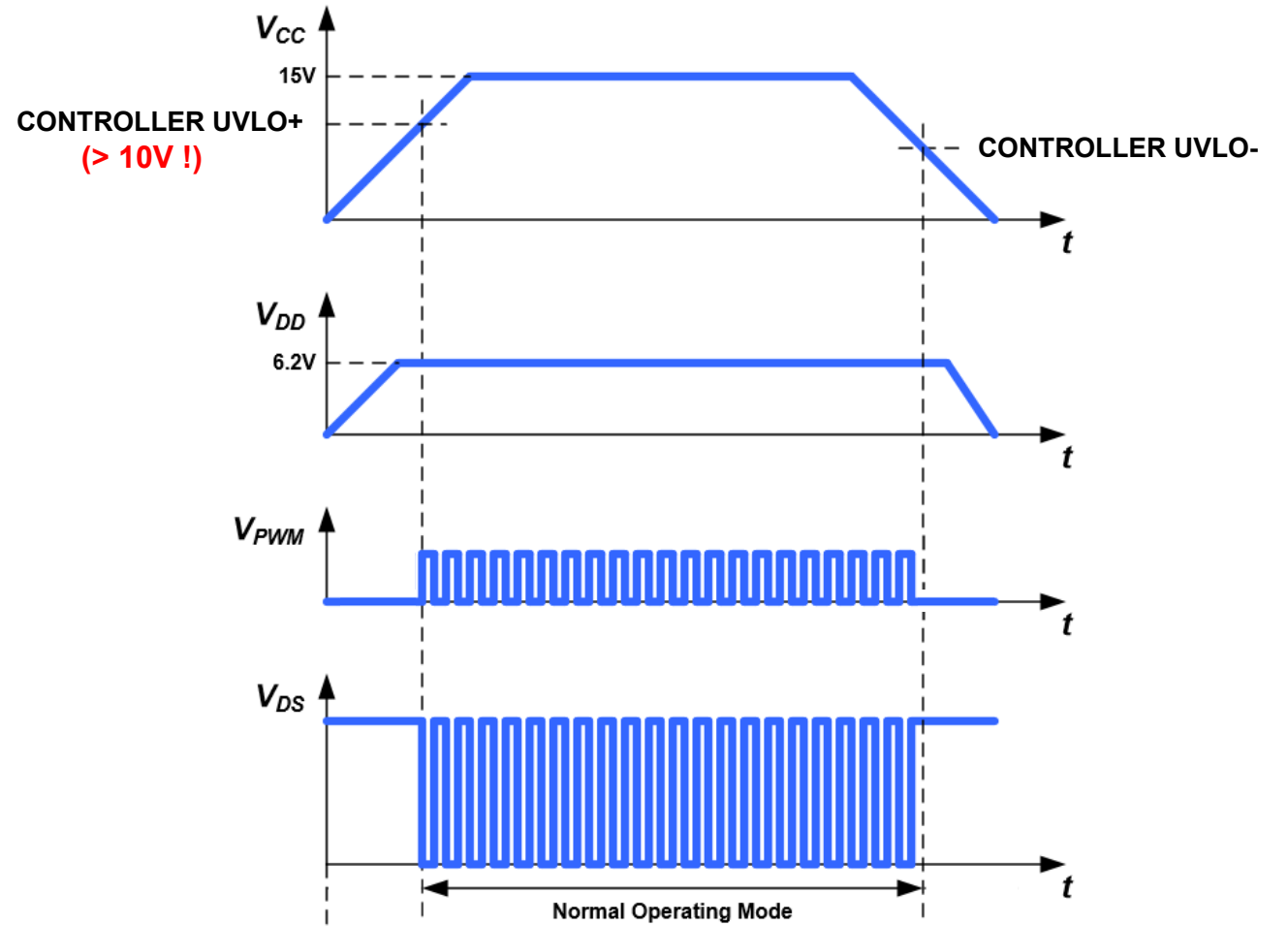


Fig 2. Normal operating mode timing diagram



NV6115 (Turn-on Slew Rate Control)

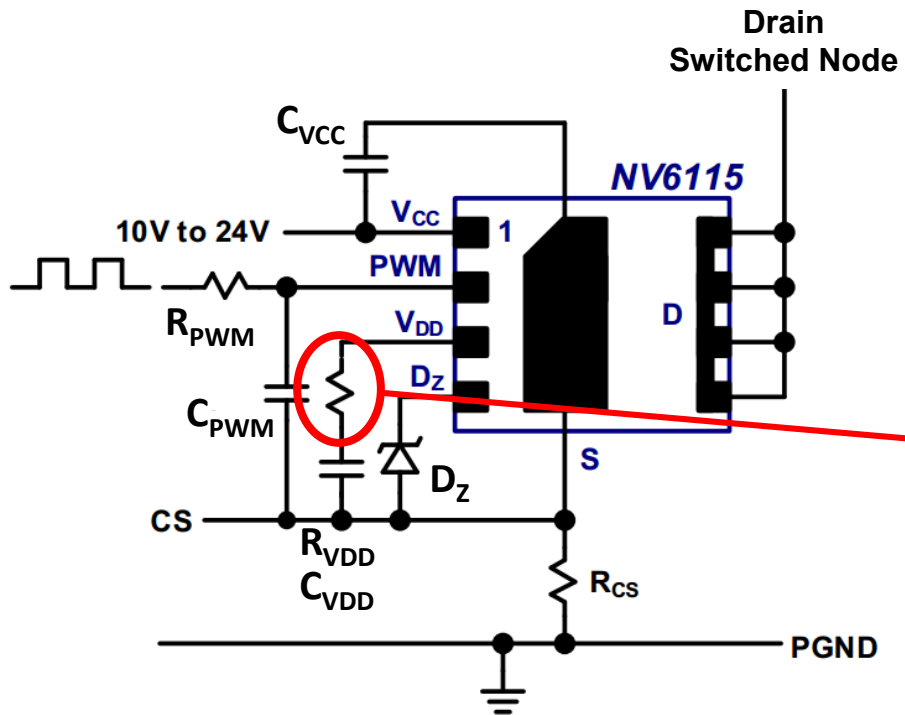


Fig 1. GaN Power IC connection diagram

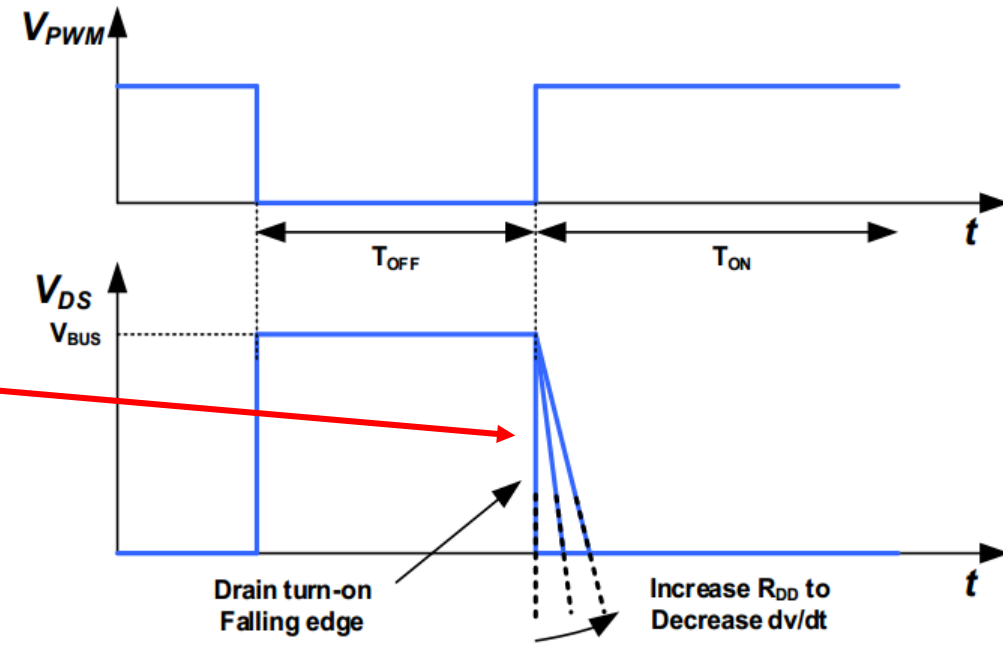
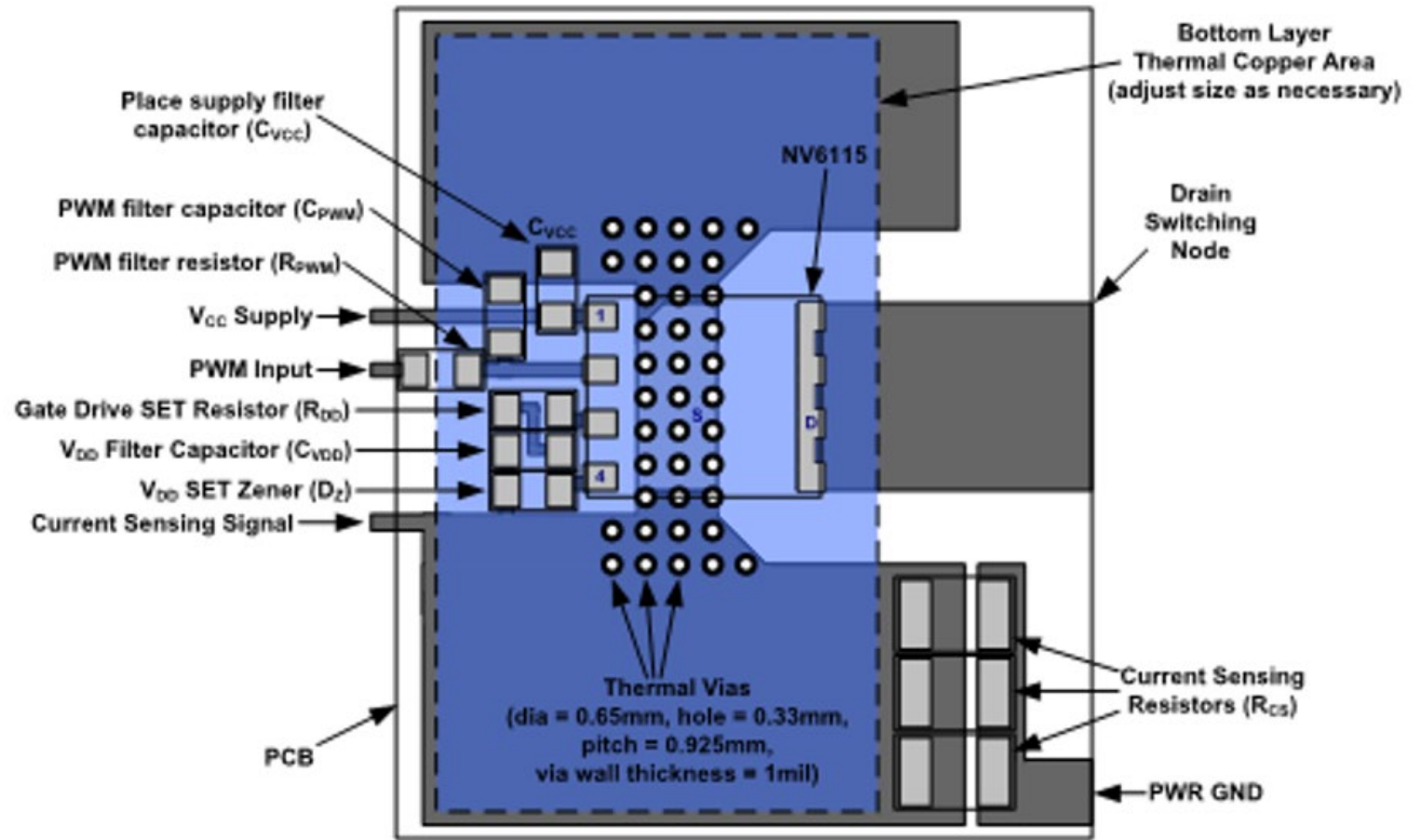
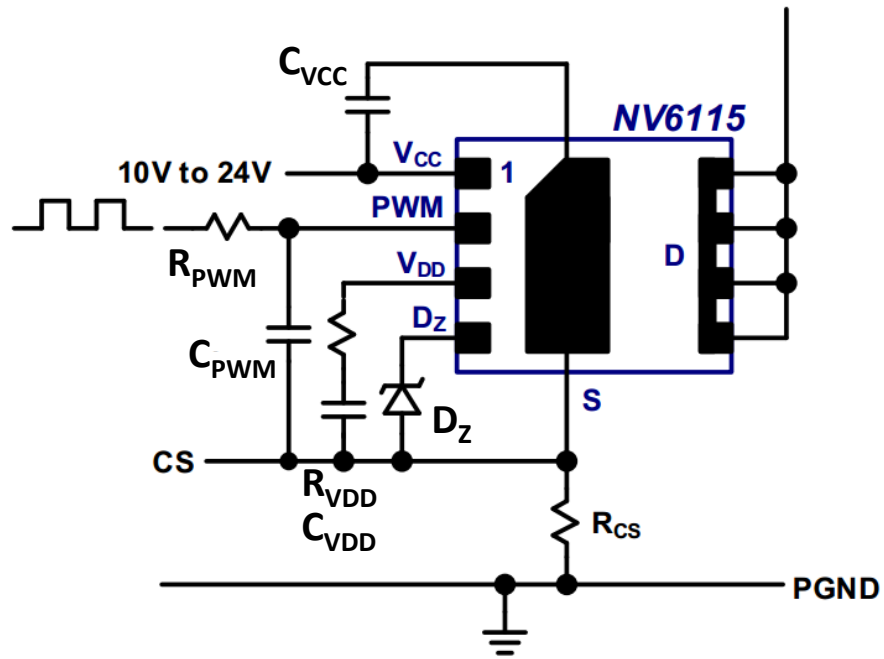


Fig 2. Turn-on Slew rate control timing diagram



NV6115 (PCB Layout)

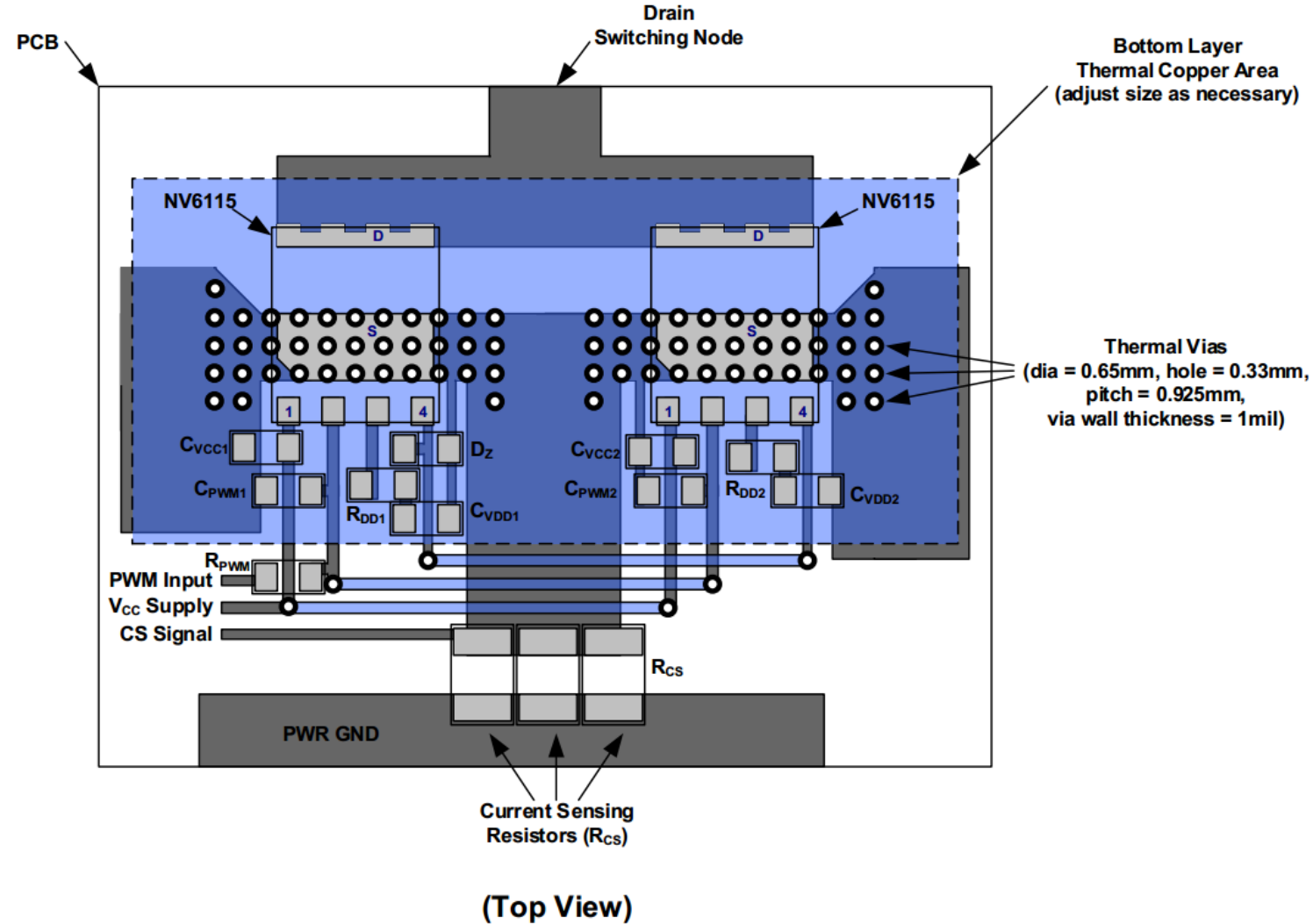
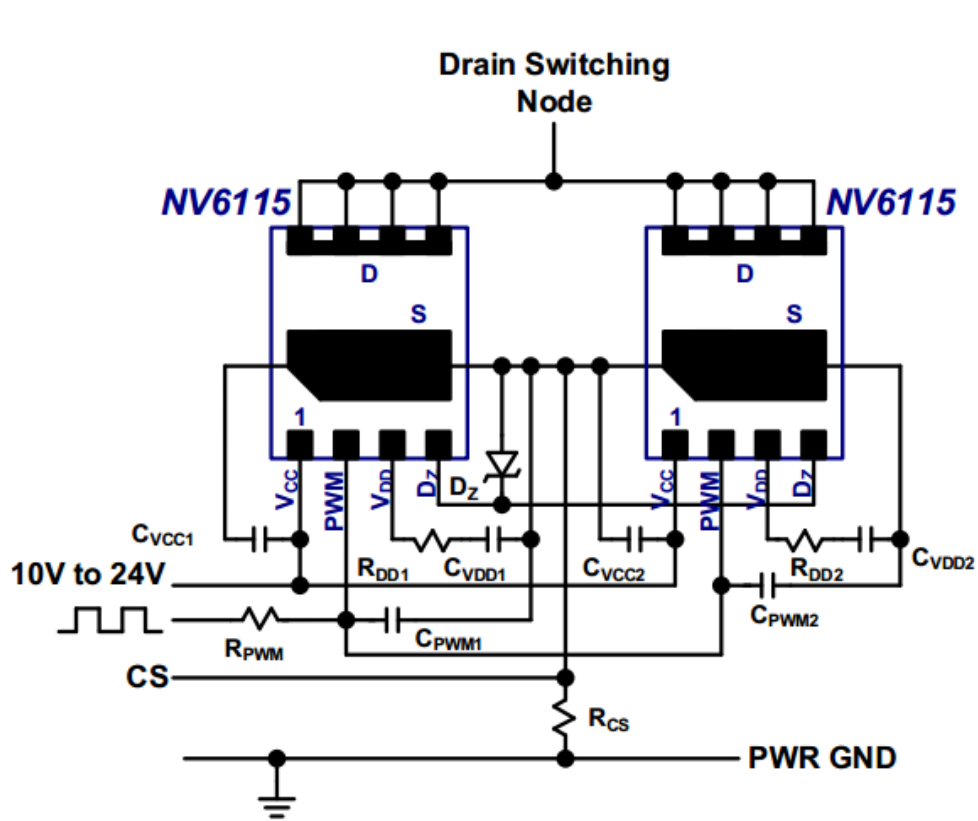


(Top View)



NV6115 (Parallel Configuration)

See datasheet for details and conditions

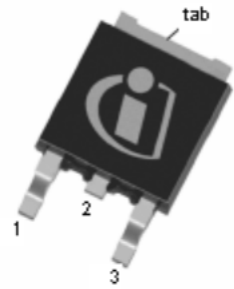




Powertrain GaN vs. Si



DPAK



IPD60R180P7

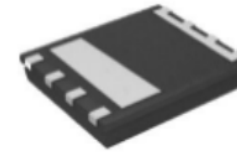
Table 1 Key Performance Parameters

Parameter	Value	Unit
$V_{DS} @ T_{j,max}$	650	V
$R_{DS(on),max}$	180	mΩ
$Q_{g,typ}$	25	nC
$I_{D,pulse}$	53	A
$E_{oss} @ 400V$	2.9	μJ
Body diode di_f/dt	900	A/μs

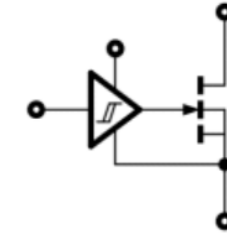
Type / Ordering Code	Package	Marking	Related Links
IPD60R180P7	PG-TO 252-3	60R180P7	see Appendix A

Table 5 Dynamic characteristics

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Input capacitance	C_{iss}	-	1081	-	pF	$V_{GS}=0V, V_{DS}=400V, f=250kHz$
Output capacitance	C_{oss}	-	19	-	pF	$V_{GS}=0V, V_{DS}=400V, f=250kHz$
Effective output capacitance, energy related ¹⁾	$C_{\alpha(er)}$	-	36	-	pF	$V_{GS}=0V, V_{DS}=0...400V$
Effective output capacitance, time related ²⁾	$C_{\alpha(t)}$	-	381	-	pF	$I_b=constant, V_{GS}=0V, V_{DS}=0...400V$



QFN 5 x 6 mm



Simplified schematic

NV6117

GaN FET Characteristics

Parameter	Symbol	Value	Unit	Test Condition
Drain-Source Leakage Current	I_{DSS}	0.3	25	μA $V_{DS} = 650V, V_{PWM} = 0V$
Drain-Source Leakage Current	I_{DSS}	10		μA $V_{DS} = 650V, V_{PWM} = 0V, T_c = 125^\circ C$
Drain-Source Resistance	$R_{DS(on)}$	120	170	mΩ $V_{PWM} = 6V, I_D = 6A$
Source-Drain Reverse Voltage	V_{SD}	3.2	5	V $V_{PWM} = 0V, I_{SD} = 6A$
Output Charge	Q_{OSS}	27		nC $V_{DS} = 400V, V_{PWM} = 0V$
Reverse Recovery Charge	Q_{RR}	0		nC
Output Capacitance	C_{OSS}	27		pF $V_{DS} = 400V, V_{PWM} = 0V$
Effective Output Capacitance, Energy Related	$C_{\alpha(er)}$	41		pF $V_{DS} = 400V, V_{PWM} = 0V$
Effective Output Capacitance, Time Related	$C_{\alpha(t)}$	67		pF $V_{DS} = 400V, V_{PWM} = 0V$

Total Gate Charge	Q_G	1.5	nC	$V_{GS} = 0 \text{ to } 6V$ $V_{DS} = 400V$
Gate-to-Source Charge	Q_{GS}	0.55	nC	
Gate-to-Drain Charge	Q_{GD}	0.40	nC	



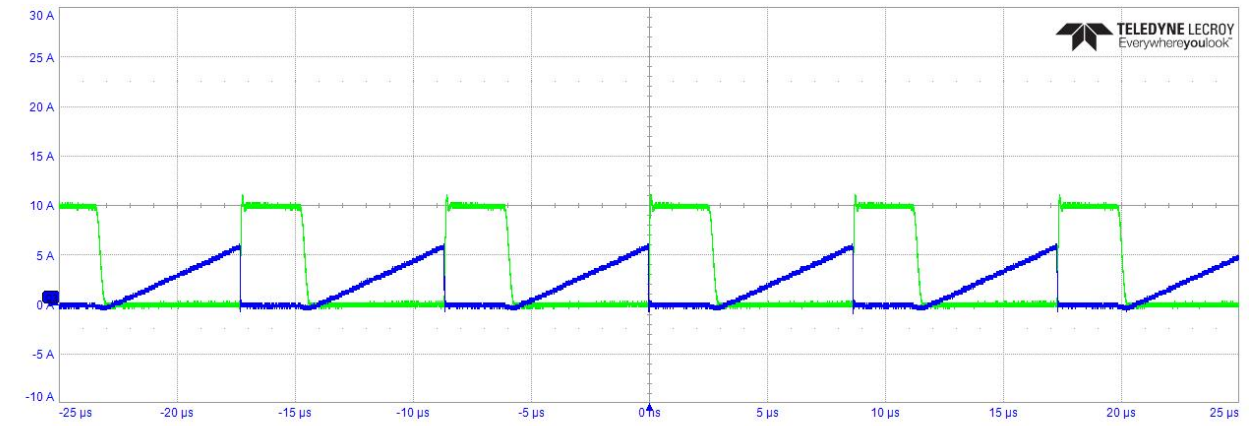
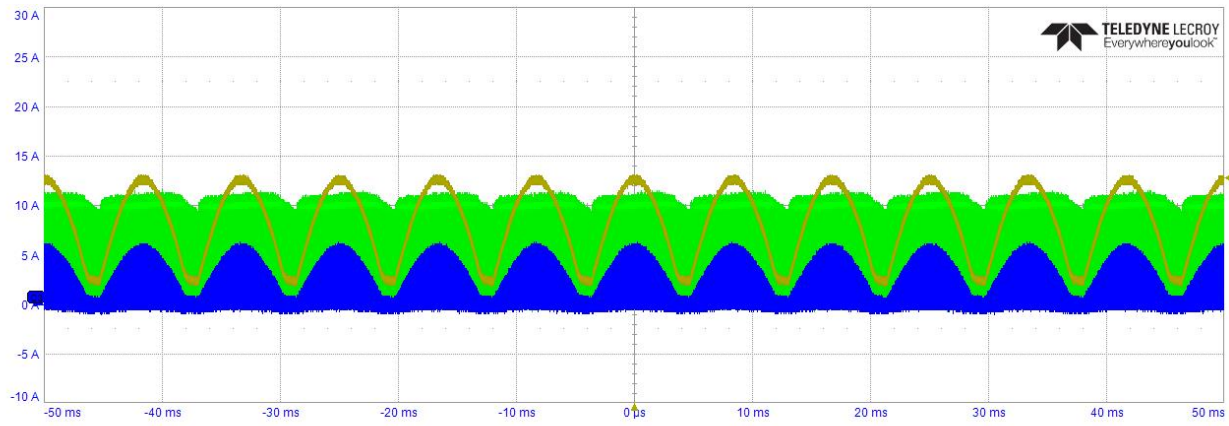
PFC Waveform Comparison



Test condition:

Input: 90 VAC, Output Voltage: 19.5V, Output Current 7.69 A

Zoom In 



Measure value status	P1:mean(C3)	P2:freq(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
	991 mA							
C1	DCIM	C2	DCIM	C3	DCIM	C4	DCIM	
50.0 V/div	5.00 A/div	200 V/div	5.00 A/div	200 V/div	5.00 A/div	200 V/div	5.00 A/div	
-100.0 V	-10.00 A	-400.0 V	-10.00 A	-400.0 V	-10.00 A	-400.0 V	-10.00 A	

Measure value status	P1:mean(C3)	P2:freq(C3)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
	1.71 A							
C1	DCIM	C2	DCIM	C3	DCIM	C4	DCIM	
5.00 A/div	5.00 A/div	200 V/div	5.00 A/div	200 V/div	5.00 A/div	200 V/div	5.00 A/div	
-10.00 A	-10.00 A	-400.0 V	-10.00 A	-400.0 V	-10.00 A	-400.0 V	-10.00 A	

Green: Vds
Blue: Id

Green: Vds

Blue: Id

Yellow: Voltage after the bridge

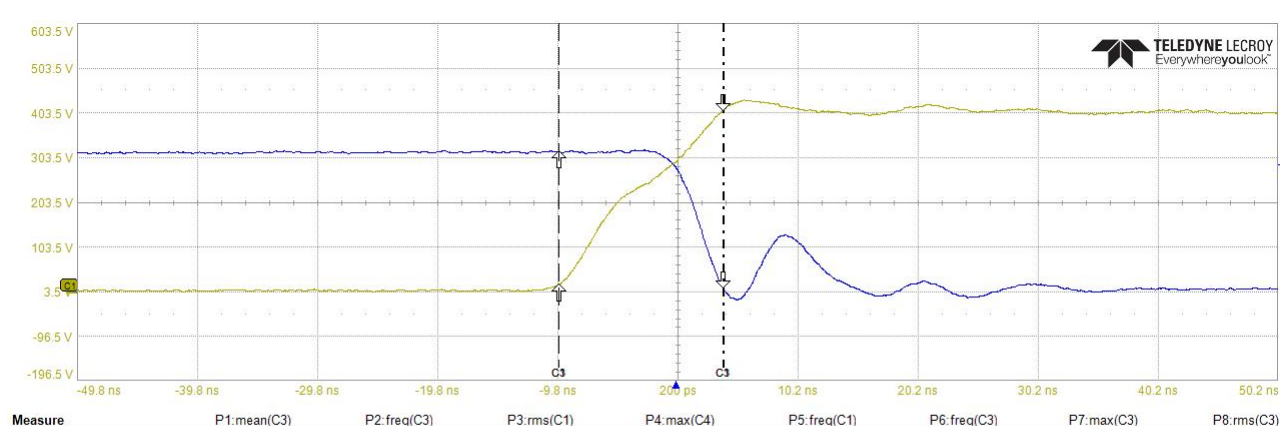


PFC Waveform Comparison



Test condition:

Input: 90 V_{AC}, Output Voltage: 19.5 V, Output Current 7.69 A

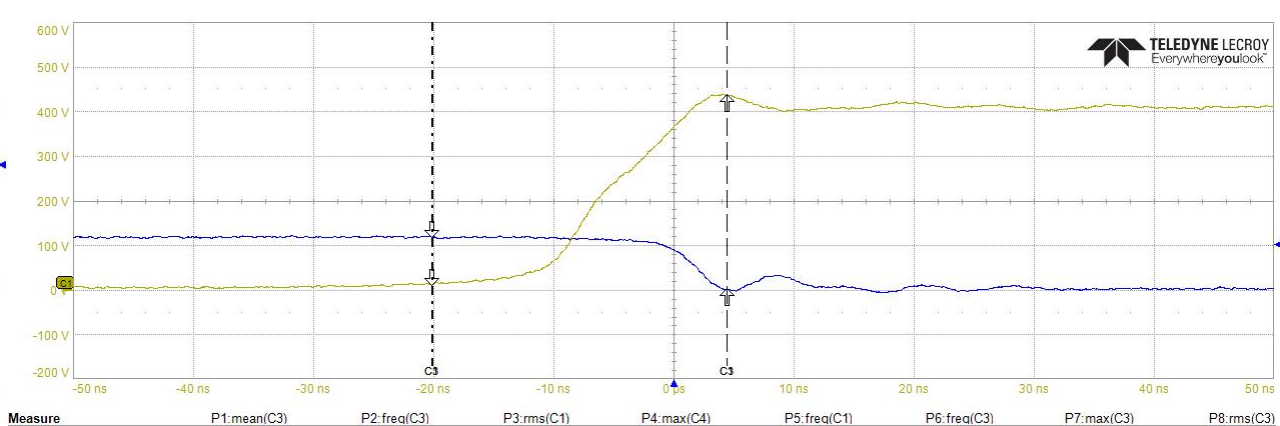


Measure	P1.mean(C3)	P2.freq(C3)	P3.rms(C1)	P4.max(C4)	P5.freq(C1)	P6.freq(C3)	P7.max(C3)	P8.rms(C3)
value	3.354 A							
status	✓							

Yellow: Vds
Blue: Id

NV6117
13.65 ns

Tbase	-200 ps	Trigger	C3	DC
	10.0 ns/div	Stop	5.70 A	
	2 kS	20 GS/s	Edge	Neg
X1=	4.00 ns	ΔX=	-13.65 ns	
X2=	-9.65 ns	1/ΔX=	-73.3 MHz	



Measure	P1.mean(C3)	P2.freq(C3)	P3.rms(C1)	P4.max(C4)	P5.freq(C1)	P6.freq(C3)	P7.max(C3)	P8.rms(C3)
value	3.11 A							
status	✓							

Yellow: Vds
Blue: Id

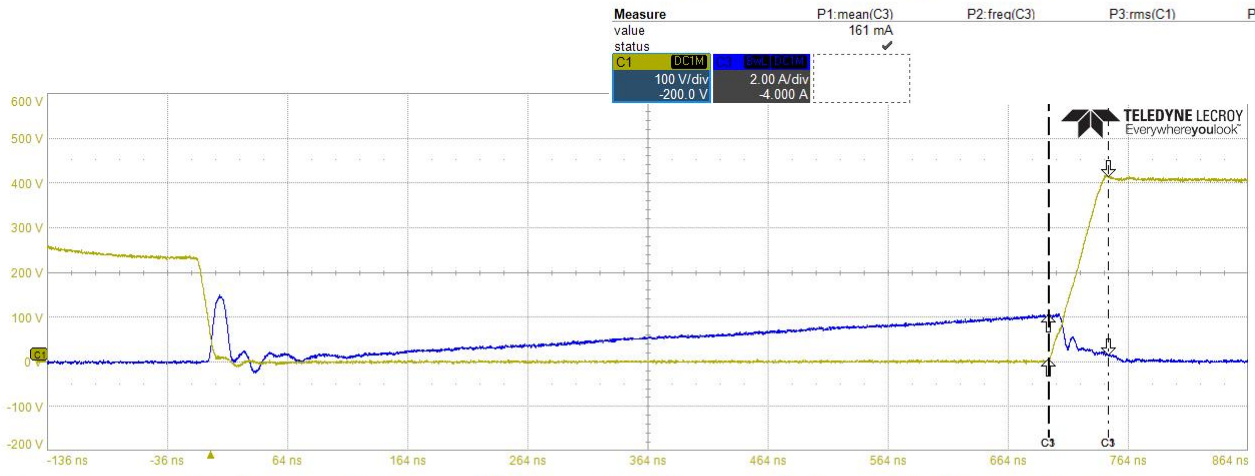
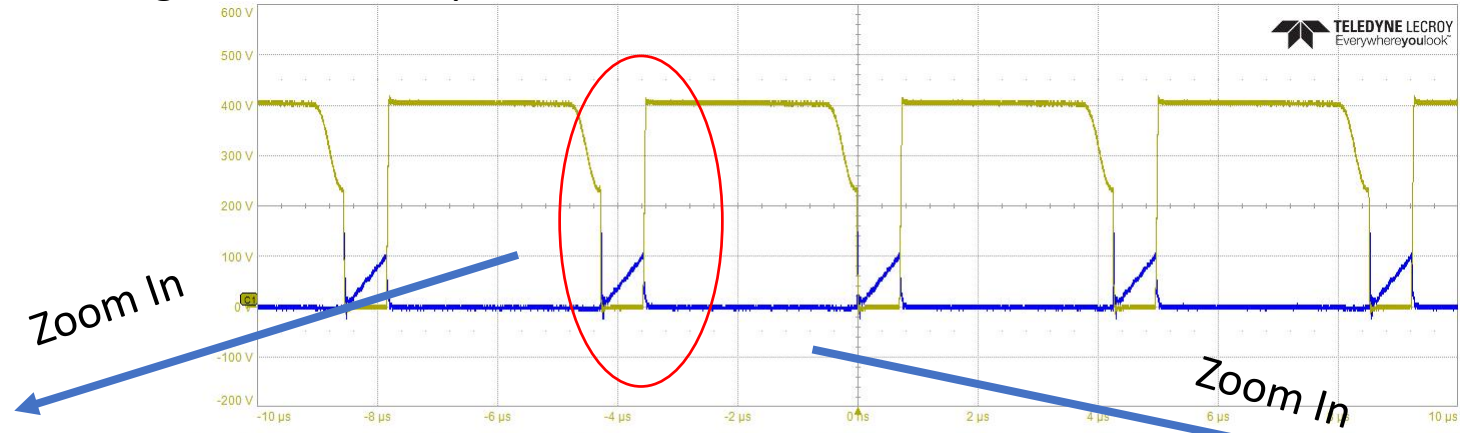
IPD60R180P7
24.6 ns

Timebase	0.0 ns	Trigger	C3	DC
	10.0 ns/div	Stop	5.15 A	
	2 kS	20 GS/s	Edge	Neg
X1=	-20.15 ns	ΔX=	24.60 ns	
X2=	4.45 ns	1/ΔX=	40.65 MHz	

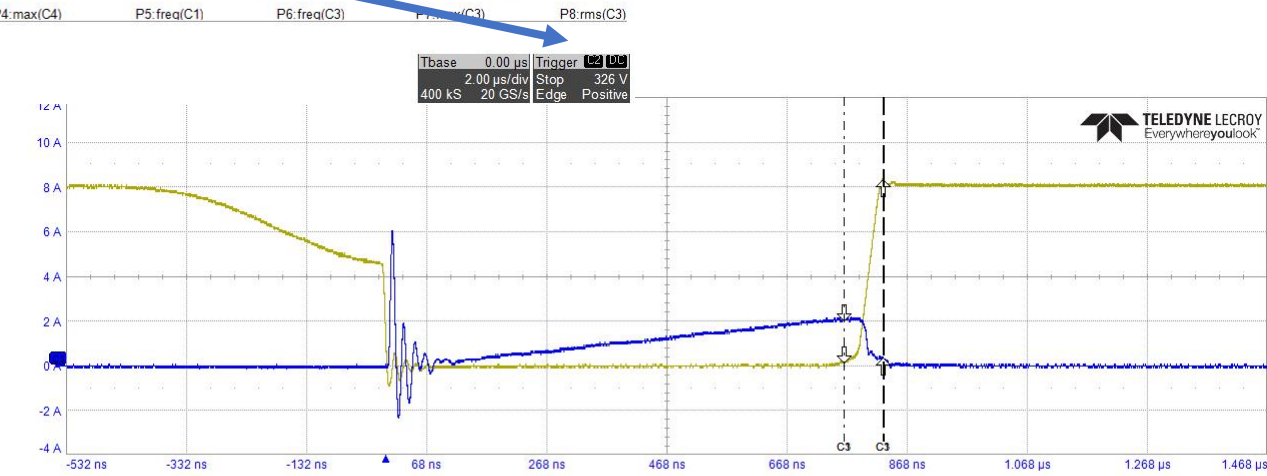


PFC Waveform Comparison

Input: 230 V_{AC}, Output Voltage: 19.5 V, Output Current 7.69 A



Yellow: Vds
Blue: Id
NV6117
49.8 ns



Yellow: Vds
Blue: Id
IPD60R180P7
65.8 ns

Measure value status	DCIM	DCIM
C1	100 V/div	2.00 A/div
	-200.0 V	-4.000 A
	414.8 V	323 mA
	3.1 V	2.027 A
Δy	-411.8 V	1.704 A

Measure value status	DCIM	DCIM
C1	100 V/div	2.00 A/div
	-200.0 V	-4.000 A
	411.9 V	292 mA
Δy	403.5 V	-1.733 A

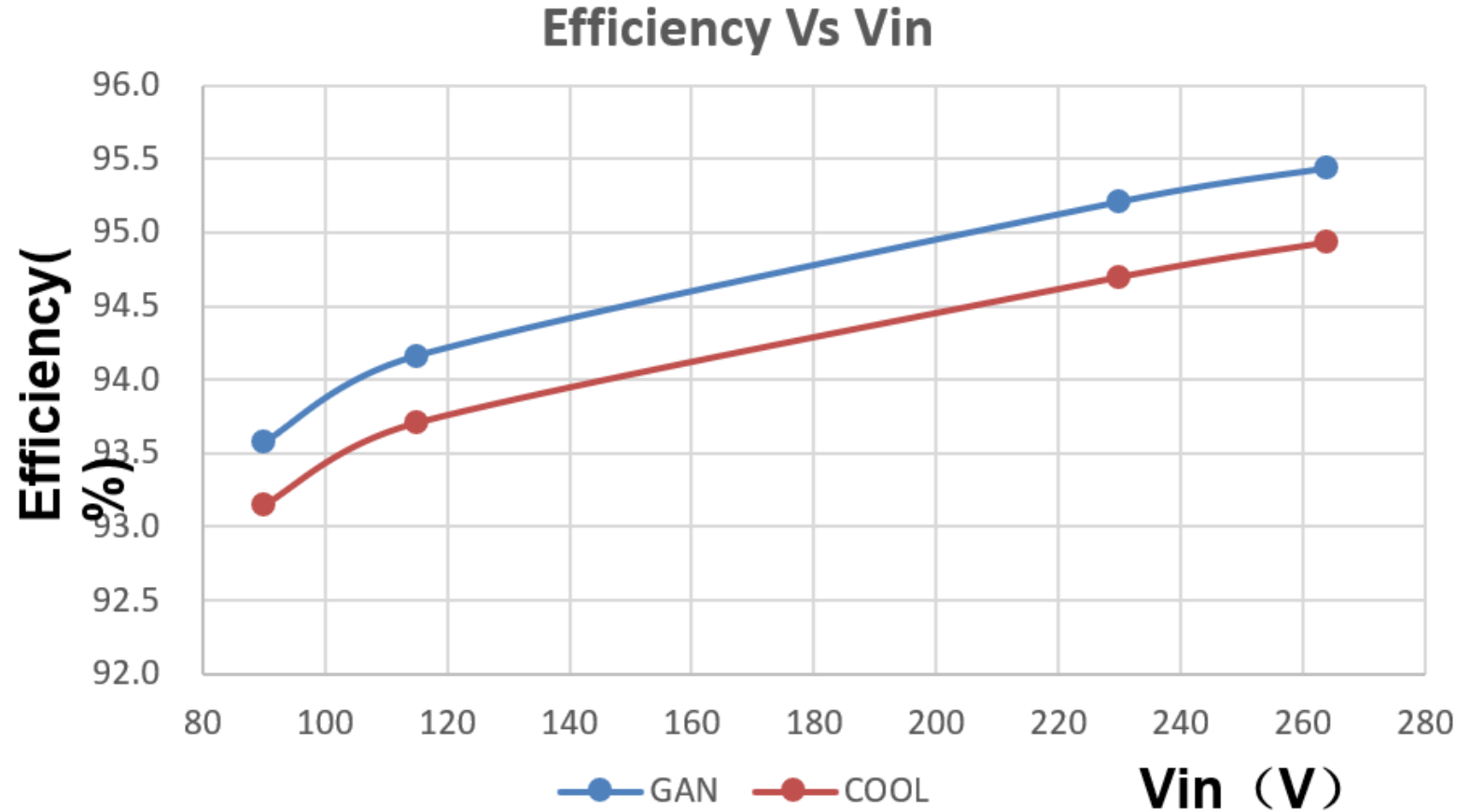
Measure value status	DCIM	DCIM
C1	100 V/div	2.00 A/div
	-200.0 V	-4.000 A
	411.9 V	292 mA
Δy	403.5 V	-1.733 A



PFC Efficiency: GaN vs. Si



Room ambient , $T_a=25^\circ\text{C}$:



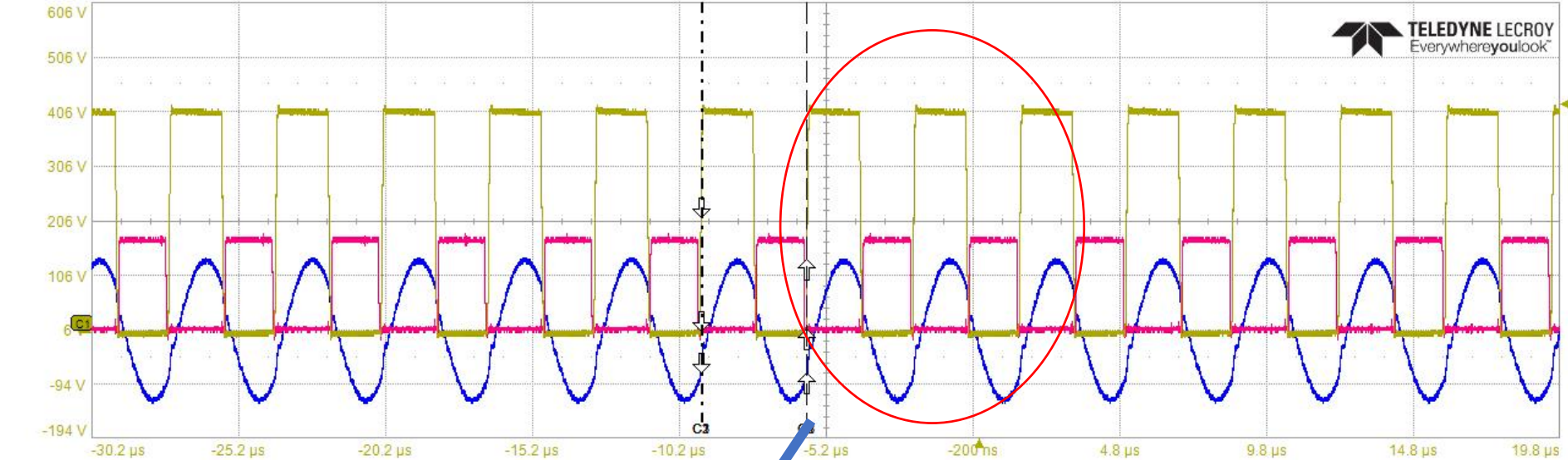
Conclusion: GaN Power IC has much lower C_{OSS} , and faster turn-off, for higher efficiency



LLC Waveform Comparison

Test condition:

Input: 230 V_{AC}, Output Voltage: 19.5 V, Output Current 7.69 A



Measure	P1:rms(C3)	P2:rms(C1)	P3:rms(C1)	P4:max(C4)	P5:freq(C1)	P6:freq(C3)	P7:max(C3)	P8:rms(C3)
value	929 mA	282.6 V						
status	✓	✓						

C1	DC1M	C2	DC1M	C3	DC1M
100 V/div	10.0 V/div	1.00 A/div			
-206.0 V	-20.00 V	-2.000 A			
↓ 211.7 V	↓ -120 mV	↓ -776 mA			
↑ 131.0 V	↓ -220 mV	↓ -822 mA			
Δy -80.7 V	Δy -100 mV	Δy -45 mA			

Timebase	5.2 μs	Trigger	C1 DC
	5.00 μs/div	Single	419 V
	500 kS	10 GS/s	Edge Neg
X1=	-9.4449 μs	ΔX=	3.6072 μs
X2=	-5.8377 μs	1/ΔX=	277.223 kHz

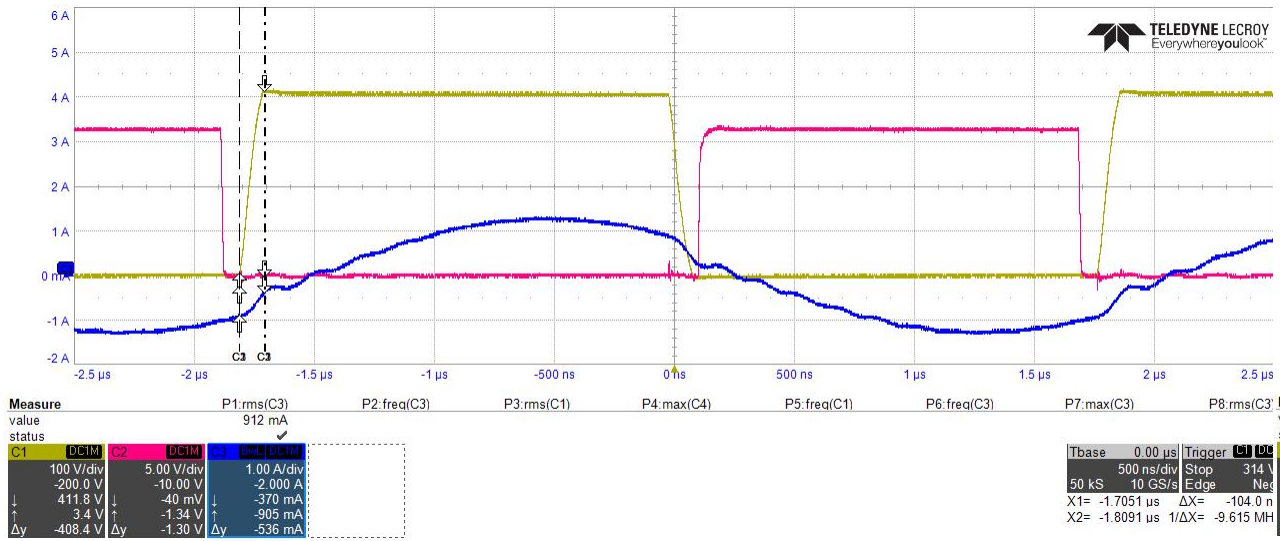
Yellow: Low Side GaN Vds
 Blue: Resonant Current
 Red Low Side Driver

Zoom In on next page

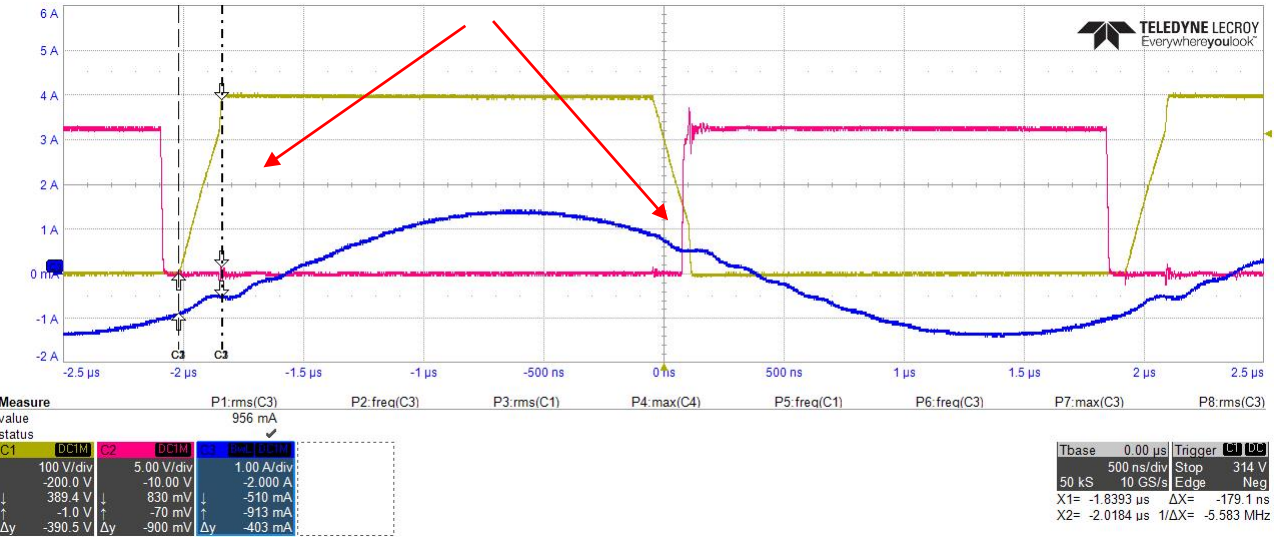


LLC Waveform Comparison

Test condition: Input: 230 V_{AC}, Output Voltage: 19.5 V, Output Current 7.69 A



GaN Power IC



Si FET paralleled with 100pF added drain-source

Original (left) waveform uses GaN power IC ($C_{OSS} = 61$ pF)

If a Si FET is used ($C_{OSS} = 381$ pF), the board blows up immediately. To capture a waveform, an extra 100pF was added (drain-source) to the FET.

Conclusion: For LLC, very big Si C_{OSS} result in losing ZVS in high-frequency application



*Here come the
GaN chargers*