Quasi-resonant and fixed-frequency flyback comparison

ICE5xSAG and ICE5QSAG on 60 W power supply

About this document

Scope and purpose

This document attempts to make a comparison between a quasi-resonant and fixed-frequency switching scheme typically used in a flyback topology. To aid the quantitative comparison, a 60 W demonstration board (P/N: DEMO_5QSAG_60W1) was modified to support both the quasi-resonant (ICE5QSAG) and fixed-frequency (ICE5ASAG) flyback controller.

Intended audience

This document is intended for power supply design or application engineers, etc. who want to design a power supply with quasi-resonant or fixed frequency in a flyback topology.

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1 Introduction

For low output power applications, the flyback converter is the most widely used topology when galvanic isolation and/or multiple output are required because it has a low system cost and is easy to design. It is used as main power supply for lower-power appliances and devices (e.g. TVs, set-top boxes, chargers/adapters, etc.) and auxiliary power supplies for higher-power applications (e.g. air-con, PC power, server power, industrial SMPS, etc.). A simplified multi-output flyback converter block diagram is shown in Figure 1.

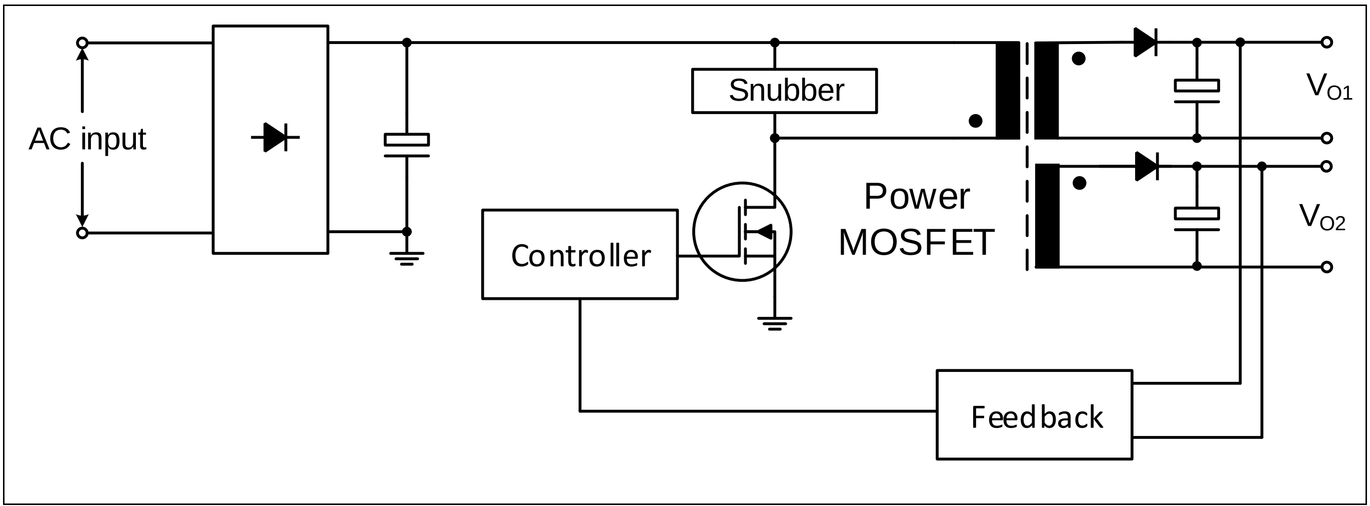


Figure 1 Simplified multi-output flyback converter block diagram

1.1 Flyback switching modes

The two common switching modes of operation of flyback are Fixed Frequency (FF) and Quasi Resonant (QR). The choice of switching mode depends on many factors such as power, efficiency, form factor, development time and so on.

1.1.1 Fixed-frequency flyback

As the name suggests, FF flyback switches come in a pre-defined fixed switching frequency. They can operate either in Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM).

In DCM, the energy stored in the transformer is completely transferred to the secondary. In CCM, the energy is not completely transferred to the secondary; therefore, the secondary current I_{SEC} does not reach zero before the next switching cycle. Refer to Figure 2 for the MOSFET drain voltage (V_{DS}) primary current (I_{PRI}) and secondary current (I_{SEC}) waveforms of DCM and CCM operation.

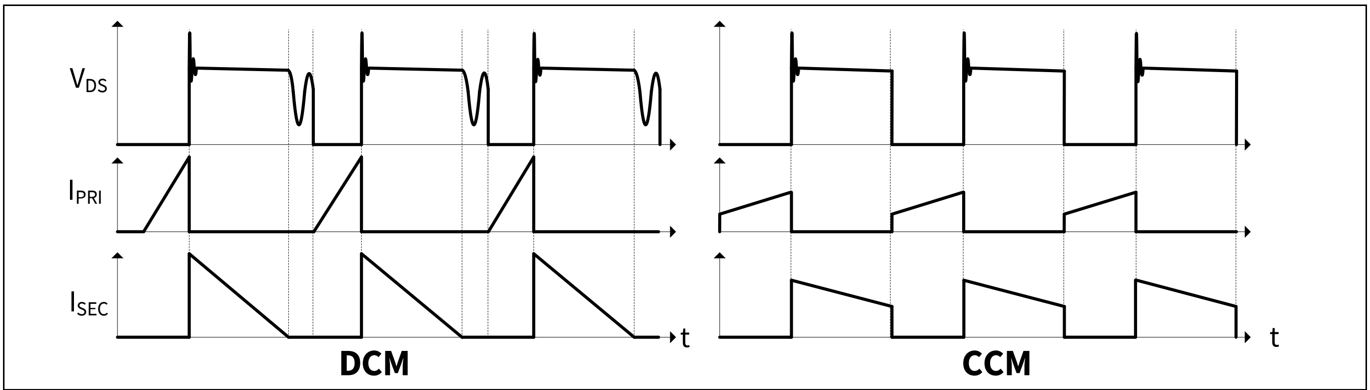


Figure 2 DCM and CCM waveforms

Infineon's fifth-generation FF controller ICE5xSAG and CoolSET™ ICE5xRxxxAG implemented a frequency reduction from mid-load to light load (see Figure 3). This scheme reduces the switching losses and improves the efficiency at lower load. Most of the controllers on the market operate with a single switching frequency across the whole load range.

Aside from frequency reduction, Active Burst Mode (ABM) is also implemented in Infineon's fifth-generation FF to meet the low standby power and very light load efficiency. ABM has three selectable entry/exit power levels (including disable ABM).

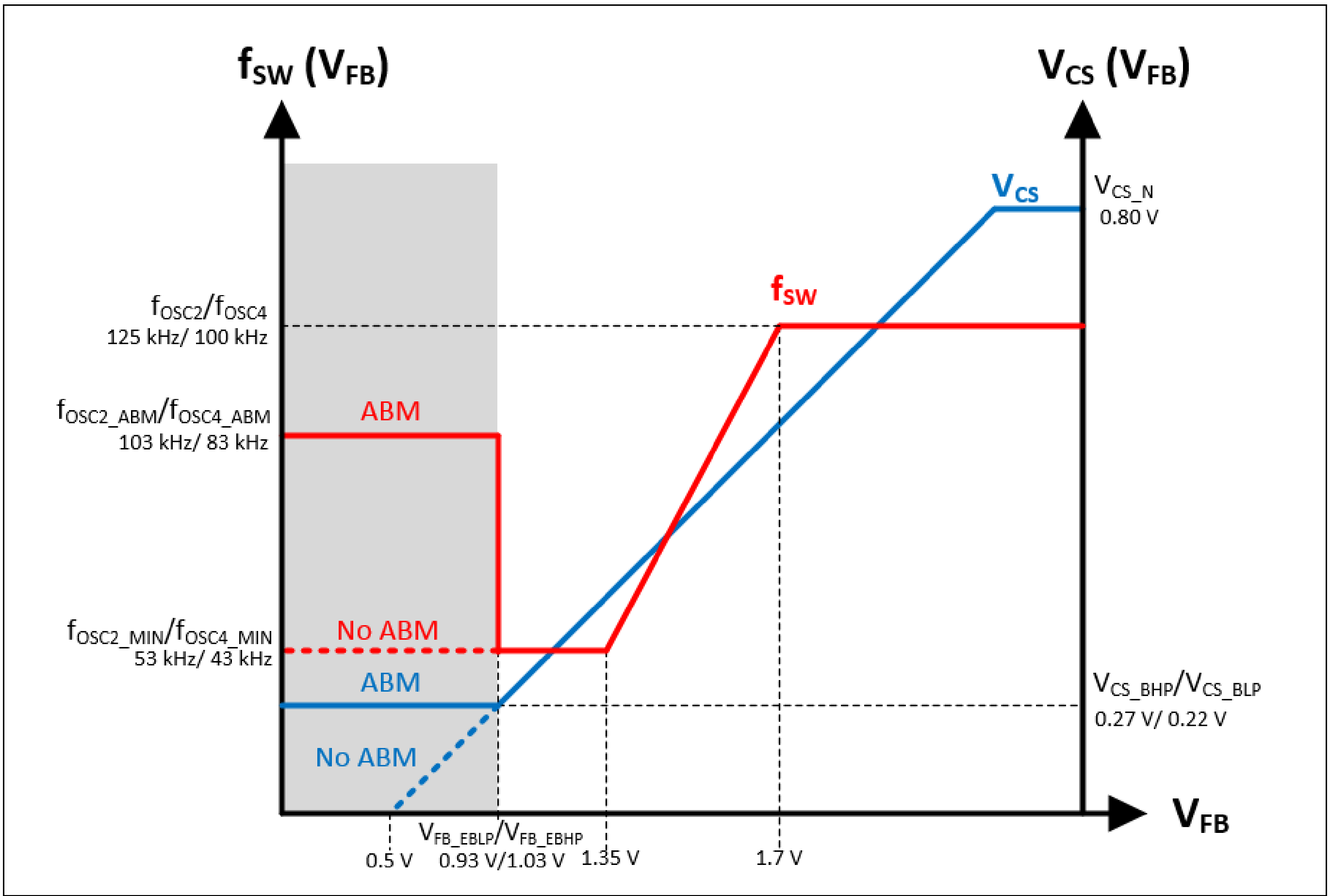


Figure 3 **Fifth-generation FF frequency reduction as function of V_{FB}**

1.1.2 QR flyback

After the energy stored in the transformer is fully discharged to the secondary, oscillation occurs across the MOSFET drain. This is caused by the primary inductance and the capacitance seen across the MOSFET drain-to-source. The voltage ringing, which depends on the reflected voltage V_R, will produce minimum valley points. When the controller detects the minimum valley point, it turns on the MOSFET for QR or valley switching flyback operation. See Figure 4 for the MOSFET V_{DS}, I_{PRI} and I_{SEC} waveforms of QR operation.

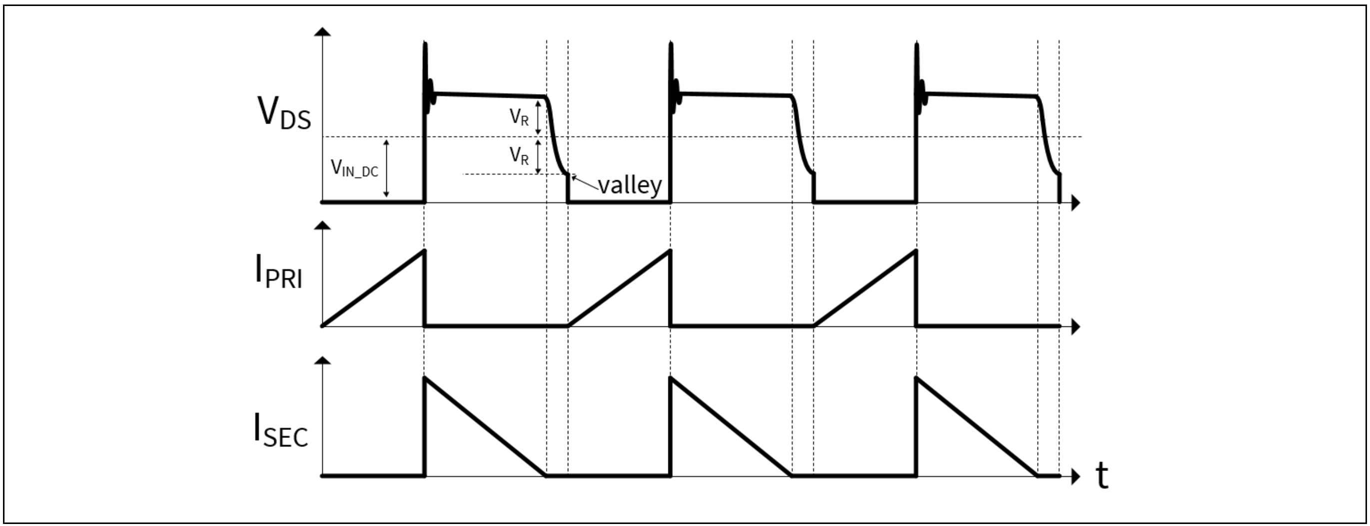


Figure 4 **QR waveforms**

QR switching frequency is variable. The switching frequency of a conventional QR controller increases exponentially as the load decreases. Infineon's fifth-generation QR controller ICE5QSAG and CoolSET™ ICE5QRxxxAx implemented a new QR switching scheme with digital frequency reduction to prevent the switching frequency from increasing significantly; therefore, switching losses are minimized. Furthermore, the IC enters ABM at light load to limit the switching frequency and achieves the lowest standby power. During ABM, the operation is still operating in QR mode. Figure 5 shows an example of the switching frequency curve of the fifth-generation QR compared to a conventional QR controller.

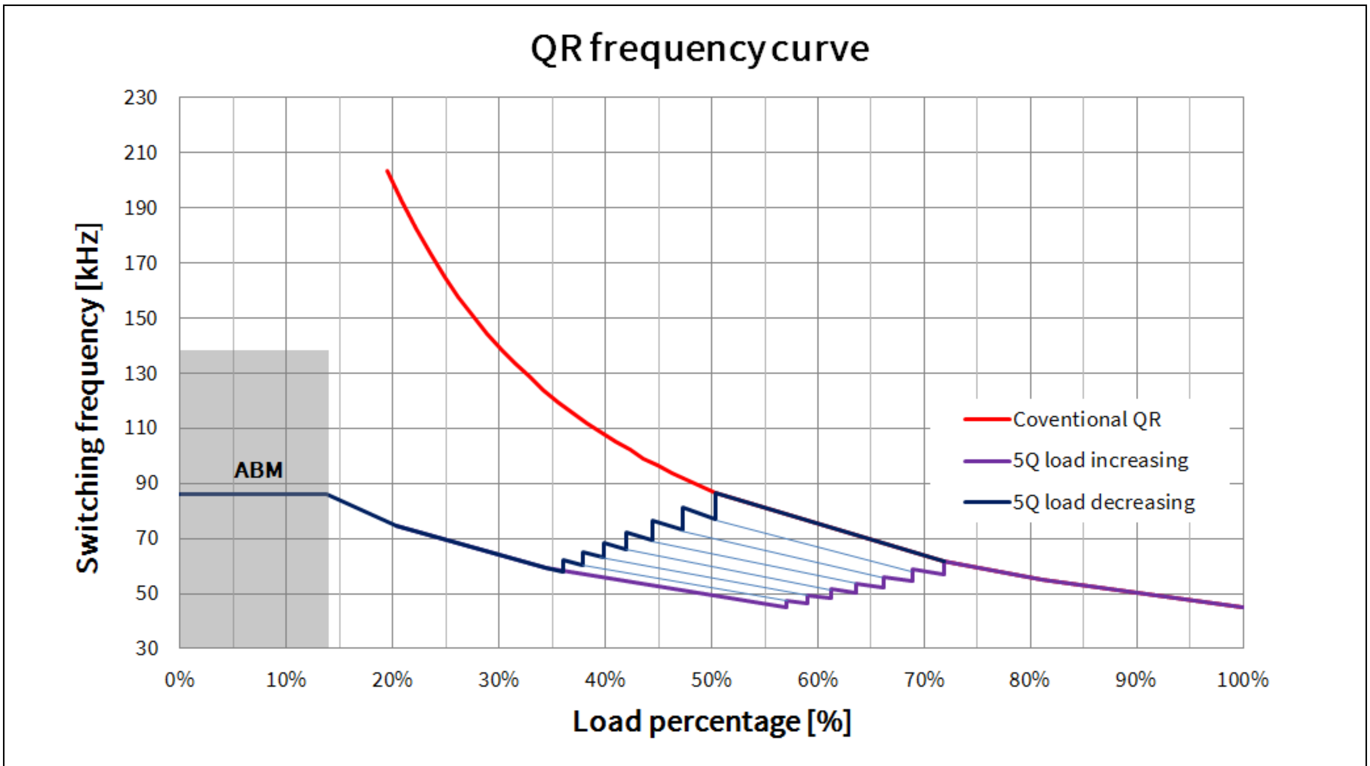


Figure 5 **Example of fifth-generation QR vs conventional QR flyback frequency curve**

1.1.3 FF DCM, FF CCM and QR advantages and disadvantages

The table below lists the advantages and disadvantages of each flyback switching mode. This can vary depending on different conditions.

Table 1

Application parameter	FF DCM	FF CCM	QR
MOSFET conduction loss, transformer winding loss and output diode conduction loss	Highest • high primary peak current results in high RMS current	Low • low primary peak current results in low RMS current	High • comparable to FF DCM at full load • lower loss than FF DCM at lower load because peak current is lower due to increasing frequency
Output diode reverse recovery loss (transition from conducting to blocking state)	Virtually zero • zero current before diode blocking state • use of fast diode is possible	High • non-zero current before diode blocking state • ultrafast or Schottky diode is necessary	Virtually zero • zero current before diode blocking state • use of fast diode is possible
MOSFET switch-on loss	Low • C_{OSS} loss • no switch-on loss due to zero drain current	Highest • C_{OSS} loss plus switch-on loss (non-zero drain current)	Lowest • C_{OSS} loss with minimum valley point switching • no switch-on loss due to zero drain current • possibility of ZVS by higher reflected voltage design
Output capacitor	Big • high ripple current • high ripple voltage	Smallest • low ripple current • low ripple voltage	Big • high ripple current • high ripple voltage • has AC ripple on output
Feedback and current loop stability design	Easy • slope compensation not required	Hard • requires slope compensation to avoid subharmonic oscillation at more than 50 percent duty cycle	Medium • slope compensation not required • need to consider variable frequency
Transformer design	Easy • smaller transformer	Medium • bigger transformer because of higher	Easy • additional winding for valley detection

Application parameter	FF DCM	FF CCM	QR
		inductance design	
Operating frequency	Fixed	Fixed	Variable • check EMI at light load due to increasing frequency when reducing load • frequency may enter audible range during output surge power
Maximum power delivery input line dependency	Accurate	Less accurate • consider power components during output surge power	Less accurate • consider power components during output surge power
Average efficiency	Low • high conduction losses from mid to maximum load	High • lowest loss from heavy to maximum load	Best • lowest loss from light to heavy load • lowest loss at high input line
Power range	Low • up to 100 W where size and ease of design is priority	High • more than 100 W where conduction losses dominate	Medium • up to 100 W where high efficiency is required

2 Evaluation board

The evaluation board used in the performance comparison is the DEMO_5QSAG_60W1 demo board. It is designed with an ICE5QSAG controller and IPA80R600P7 CoolMOS™. It is dual-output (12 V/4.58 A and 5 V/1 A) with universal input (85 V AC to 300 V AC). Only 12 V output is loaded. 5 V output is disabled by not adding 5 V output winding in the transformer. Output sensing resistor R25A is de-soldered and R25 is changed to 9.5 kΩ.

In order to achieve a better comparison, only one evaluation board is used. The board can be configured between QR (ICE5QSAG) and FF (ICE5ASAG), keeping the same key components such as the input stage (EMI network, bridge diode and bulk capacitor), power conversion stage (power MOSFET and transformer) and output stage (secondary rectifier diode, output capacitors and LC filter).

Figure 6 Top view of DEMO_5QSAG_60W1

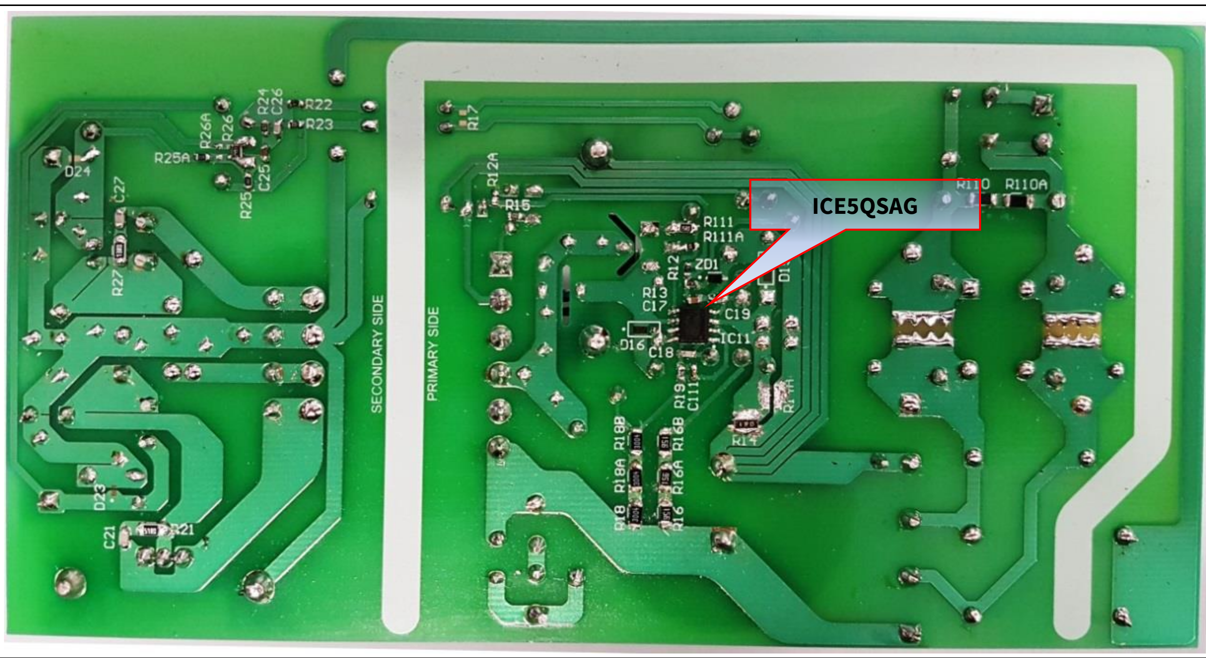


Figure 7 Bottom view of DEMO_5QSAG_60W1

2.1 Circuit diagram

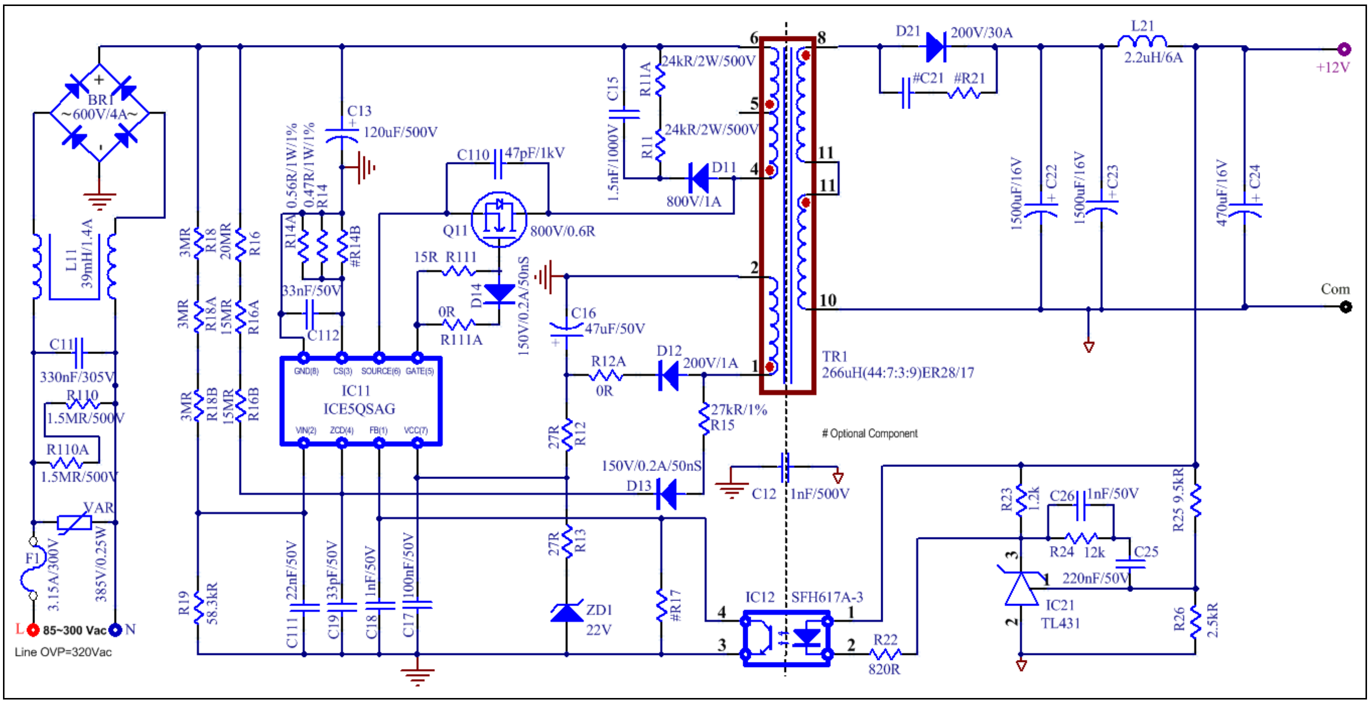


Figure 8 ICE5QSAG schematic

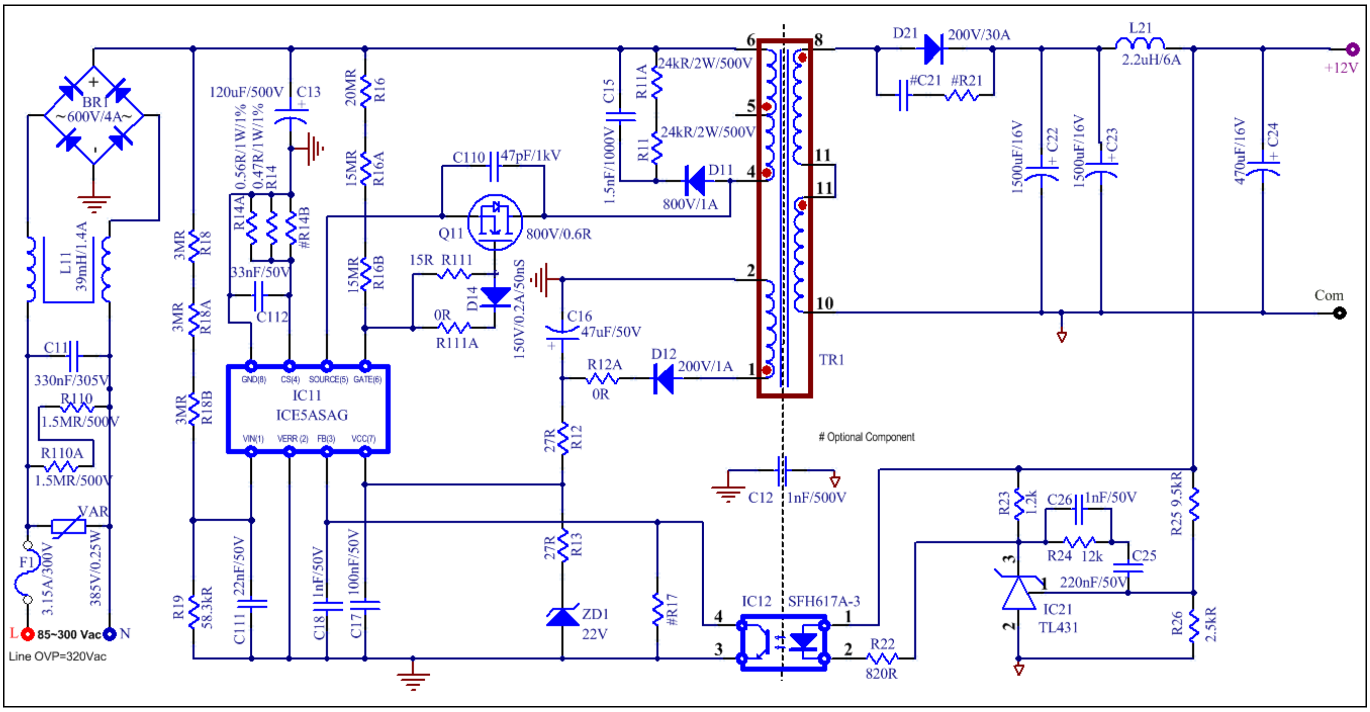


Figure 9 ICE5ASAG schematic

2.2 PCB layout

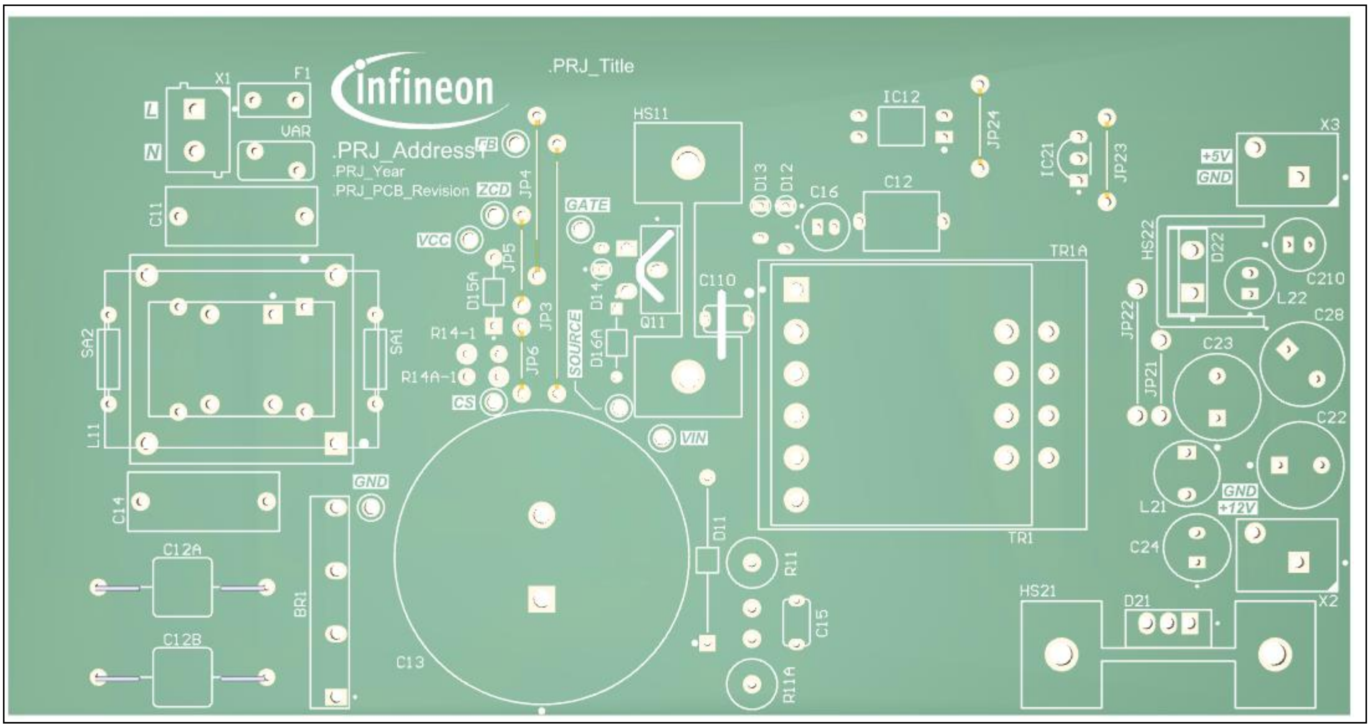


Figure 10 Top layer of DEMO_5QSAG_60W1

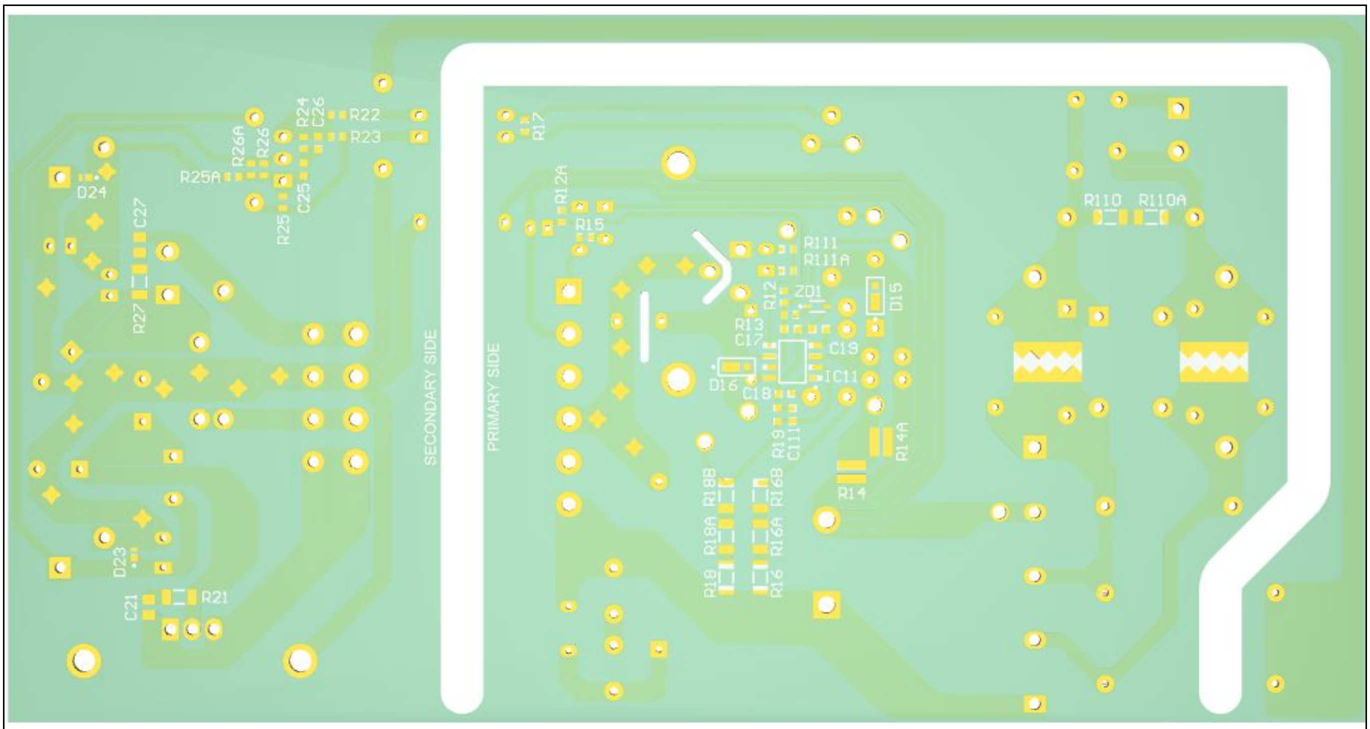


Figure 11 Bottom layer of DEMO_5QSAG_60W1

2.3 Bill of Materials (BOM)

Table 2 BOM

No.	Designator	Description	Part number	Manufacturer	Quantity
1	BR1	600 V/4 A	D4SB60L	Shindengen	1
2	C11	0.33 µF/305 V	B32922C3334M000	Epcos	1
3	C12	1 nF/500 V	DE1E3RA102MA4BQ	Murata	1
4	C13	120 µF/500 V	LGN2H121MELB30		1
5	C15	1.5 nF/1000 V	RDE7U3A152J3K1H03	Murata	1
6	C16	47 µF/50 V	35PX47MEFC5X11	Rubycon	1
7	C17	100 nF/50 V	GRM188R71H104KA93D	Murata	1
8	C18, C26	1 nF/50 V	GRM1885C1H102GA01D	Murata	2
9	C19[1]	33 pF/50 V	GRM1885C1H330GA01D	Murata	1
10	C110	47 pF/1000 V	RDE7U3A470J2K1H03	Murata	1
11	C111	22 nF/50 V	GCM188R71H223KA37D	Murata	1
12	C112	33 nF/50 V	GRM188R71H333KA61D	Murata	1
13	C22, C23	1500 µF/16 V	16ZLH1500MEFC10X20	Rubycon	2
14	C24	470 µF/16 V	16ZLH470MEFC8X11.5	Rubycon	1
15	C25	220 nF/50 V	GRM188R71H224KAC4D	Murata	1
19	D11	1 A/800 V	UF4006		1
20	D12	1 A/200 V	1N4003-E3/54		1
21	D13,[1] D14	0.2 A/150 V/50 ns	FDH400		1
22	D21	30 A/200 V	VF30200C-E3/4W		1
24	F1	3.15 A/300 V	36913150000		1
25	HS11, HS21	Heatsink	513102B02500G		2
27	IC11	ICE5QSAG	ICE5QSAG	Infineon	1
28	IC12	Optocoupler	SFH617A-3		1
29	IC21	Shunt regulator	TL431BVLPG		1
30	JP3, JP4, JP5, JP6, JP23	Jumper			5
31	L11	39 mH/1.4 A	B82734R2142B030	Epcos	1
32	L21	2.2 µH/6 A	744772022	Wurth Electronics	1
34	Q11	800 V/600 mΩ	IPA80R600P7	Infineon	1
35	R11, R11A	24 kΩ/2 W/500 V	PR02000202402JR500		2
36	R12, R13	27 Ω	0603 resistor		2
37	R12A, R111A	0 Ω	0603 resistor		2
38	R14[2]	0.47 Ω/0.75 W/±1 percent	ERJ-B2BFR47V		1
39	R14A[2]	0.56 Ω/0.75 W/±1 percent	ERJ-B2BFR56V		1
40	R15[1]	27 kΩ/±1 percent	0603 resistor		1
41	R16	20 MΩ	1206 resistor		1
42	R16A, R16B	15 MΩ	1206 resistor		2
43	R18, R18A, R18B	3 MΩ	1206 resistor		3
44	R19	58.3 kΩ/0.1 W/0.5 percent	RT0603DRE0758K3L		1
45	R110, R110A	1.5 MΩ/500 V	1206 resistor		2
46	R111	15 Ω	0603 resistor		1

[1] Not mounted in FF set-up.

[2] The current sense resistor is adjusted depending on the test required.

47	R22	820 Ω	0603 resistor		1
48	R23	1.2 kΩ	0603 resistor		1
49	R24	12 kΩ	0603 resistor		1
50	R25	9.5 kΩ	0603 resistor		1
52	R26	2.5 kΩ	0603 resistor		1
54	TR1	266 µH	750343773 (Rev. 02)	Wurth Electronics	1
55	FB, V_{IN}, CS, ZCD, GATE, SOURCE, V_{CC}, GND	Test point	5010		8
56	VAR	0.25 W/385 V	B72207S0381K101	Epcos	1
57	ZD1	22 V	DZ2J220M0L		1
58	Con (L N)	Connector	691102710002	Wurth Electronics	1
59	Con (+12 V com), Con (+5 V com)	Connector	691 412 120 002B	Wurth Electronics	2

3 QR and FF DCM comparison

3.1 Test condition and set-up

As the demonstration board (P/N: DEMO_5QSAG_60W1) was originally designed based on a QR (ICE5QSAG) controller, the transformer was designed at 40 kHz (full load at 85 V AC). To facilitate the comparison, transformer redesign is necessary to accommodate 100 kHz switching frequency of the FF controller (ICE5ASAG). The second output (+5 V) from the original design was removed to simplify the comparison.

Core: ER28/14 TP4A
Primary inductance: 120 µH

Start	Stop	No. of turns	Wire size	Layer
4	5	12	4 x AWG#28	1/2 Primary
6		5	3 x AWG#28	Shield
8	10	4	1 x TIW LITZ (120x38)	Secondary
6		5	3 x AWG#28	Shield
5	6	12	4 x AWG#28	1/2 Primary
1	2	5	1 x AWG#28	Auxiliary

Figure 12 QR and FF DCM transformer specification

Since ICE5QSAG and ICE5xSAG have different Peak Current Limitation (PCL) threshold voltage (V_{CS_N}) levels, Current Sense (CS) resistors are also changed as shown in Table 3 so that the over-load power will be as close as possible.

Table 3 ICE5QSAG and ICE5ASAG V_{CS_N} and CS resistor (R14)

Controller	V_{CS_N}	CS resistor (R14)
ICE5QSAG	1.0 V	0.273 Ω
ICE5ASAG	0.8 V	0.243 Ω

3.2 Frequency curve

When load is decreasing, QR has higher switching frequency. This can result from higher switching losses but lower conduction losses due to lower RMS current.

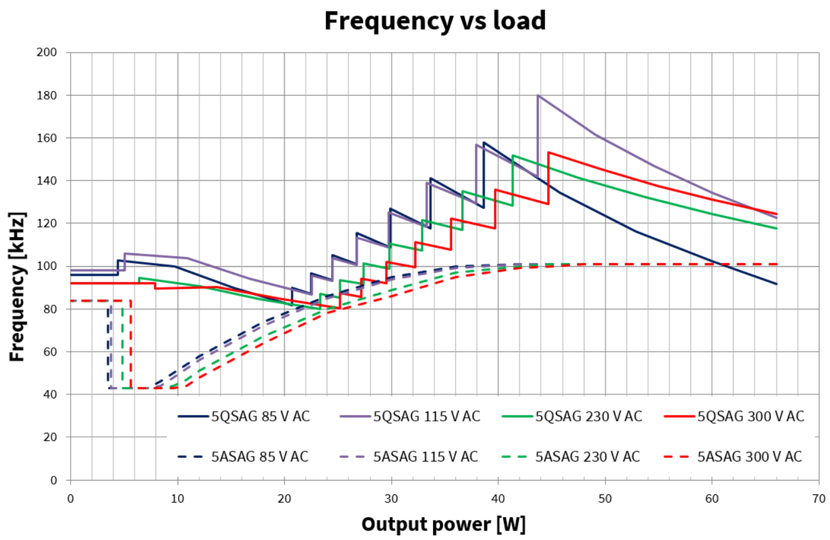


Figure 13 Frequency vs output load

3.3 Electrical test measurement

The input power is measured using WT210 power meter integration function. The sequence of measurement is from full load down to no load, which will make the QR operate at higher switching frequency.

3.3.1 Electrical test measurement

Table 4 Electrical measurement based on QR controller (ICE5QSAG with 100 kHz transformer design)

Input (V AC/ Hz)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	Efficiency (percent)	Average efficiency (percent)	OLP P_{IN} (W)	OLP I_{OUT} (A)
85 V AC/ 60 Hz	0.05933	12.0647	0.0000				85.86	5.60
	7.492	12.0635	0.5000	6.03	80.51%			
	18.180	12.0614	1.2506	15.08	82.97%	81.77%		
	36.523	12.0580	2.5018	30.17	82.60%			
	55.325	12.0548	3.7531	45.24	81.78%			
	75.630	12.0510	5.0031	60.29	79.72%			
115 V AC/ 60 Hz	0.06310	12.0647	0.0000				97.60	6.54
	7.548	12.0637	0.5000	6.03	79.91%			
	18.044	12.0617	1.2506	15.08	83.60%	83.55%		
	35.971	12.0588	2.5018	30.17	83.87%			
	53.958	12.0553	3.7531	45.24	83.85%			
	72.762	12.0517	5.0031	60.30	82.87%			
230 V AC/ 50 Hz	0.08953	12.0648	0.0000				102.12	7.01
	7.556	12.0631	0.5000	6.03	79.83%			
	18.440	12.0617	1.2506	15.08	81.80%	83.43%		
	36.098	12.0583	2.5018	30.17	83.57%			
	53.788	12.0553	3.7531	45.24	84.12%			
	71.580	12.0518	5.0031	60.30	84.24%			
265 V AC/ 50 Hz	0.10167	12.0655	0.0000				106.27	7.31
	7.639	12.0632	0.5000	6.03	78.96%			
	18.653	12.0617	1.2506	15.08	80.87%	82.91%		
	36.304	12.0583	2.5018	30.17	83.10%			
	54.108	12.0549	3.7531	45.24	83.62%			
	71.718	12.0509	5.0031	60.29	84.07%			
300 V AC/ 50 Hz	0.12098	12.0652	0.0000				109.63	7.54
	7.727	12.0632	0.5000	6.03	78.06%			
	18.898	12.0616	1.2506	15.08	79.82%	82.26%		
	36.623	12.0580	2.5018	30.17	82.37%			
	54.400	12.0548	3.7531	45.24	83.17%			
	72.048	12.0515	5.0031	60.29	83.69%			

Table 5 Electrical measurement based on FF controller (ICE5ASAG) in DCM

Input (V AC/ Hz)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	Efficiency (percent)	Average efficiency (percent)	OLP P_{IN} (W)	OLP I_{OUT} (A)
85 V AC/ 60 Hz	0.06623	12.0656	0.0000				86.56	5.66
	7.355	12.0640	0.5000	6.03	82.01%			
	18.214	12.0618	1.2506	15.08	82.82%	81.39%		
	36.733	12.0585	2.5018	30.17	82.13%			
	55.835	12.0551	3.7531	45.24	81.03%			
	75.762	12.0514	5.0031	60.29	79.58%			
115 V AC/ 60 Hz	0.07006	12.0661	0.0000				86.07	5.80
	7.344	12.0644	0.5000	6.03	82.14%			
	18.029	12.0619	1.2506	15.08	83.67%	83.06%		
	36.106	12.0586	2.5018	30.17	83.56%			
	54.557	12.0553	3.7531	45.24	82.93%			
	73.464	12.0516	5.0031	60.30	82.07%			
230 V AC/ 50 Hz	0.10061	12.0656	0.0000				87.08	6.00
	7.606	12.0641	0.5000	6.03	79.30%			
	18.285	12.0618	1.2506	15.08	82.50%	83.40%		
	36.056	12.0584	2.5018	30.17	83.67%			
	54.028	12.0551	3.7531	45.24	83.74%			
	72.048	12.0514	5.0031	60.29	83.69%			
265 V AC/ 50 Hz	0.11470	12.0652	0.0000				89.16	6.13
	7.722	12.0639	0.5000	6.03	78.11%			
	18.416	12.0617	1.2506	15.08	81.91%	83.01%		
	36.361	12.0585	2.5018	30.17	82.97%			
	54.154	12.0548	3.7531	45.24	83.54%			
	72.096	12.0512	5.0031	60.29	83.63%			
300 V AC/ 50 Hz	0.13330	12.0659	0.0000				91.10	6.25
	7.853	12.0640	0.5000	6.03	76.81%			
	18.598	12.0619	1.2506	15.08	81.11%	82.51%		
	36.686	12.0585	2.5018	30.17	82.23%			
	54.365	12.0552	3.7531	45.24	83.22%			
	72.228	12.0515	5.0031	60.29	83.48%			

3.3.2 Efficiency curve

The full-load efficiency of QR is higher than FF DCM (up to 0.8 percent at 115 V AC). This is due to lower conduction loss as a result of lower RMS currents. The lower RMS current is due to higher switching frequency and lower peak currents. The switching frequency is higher, but conduction loss dominates at higher power.

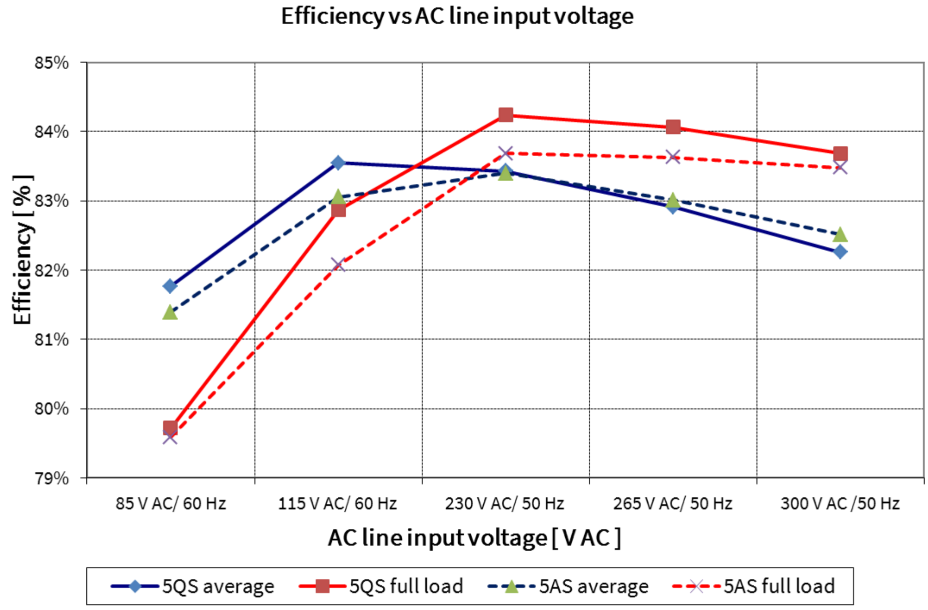


Figure 14 Average and full-load efficiency

As the load decreases, the switching loss starts to dominate, especially at higher input voltage. Therefore, the higher switching frequency of QR makes the efficiency lower, as can be seen in Figure 15. At 230 V AC, the 25 percent and 50 percent load switching frequency difference is about 30 kHz and 20 kHz respectively.

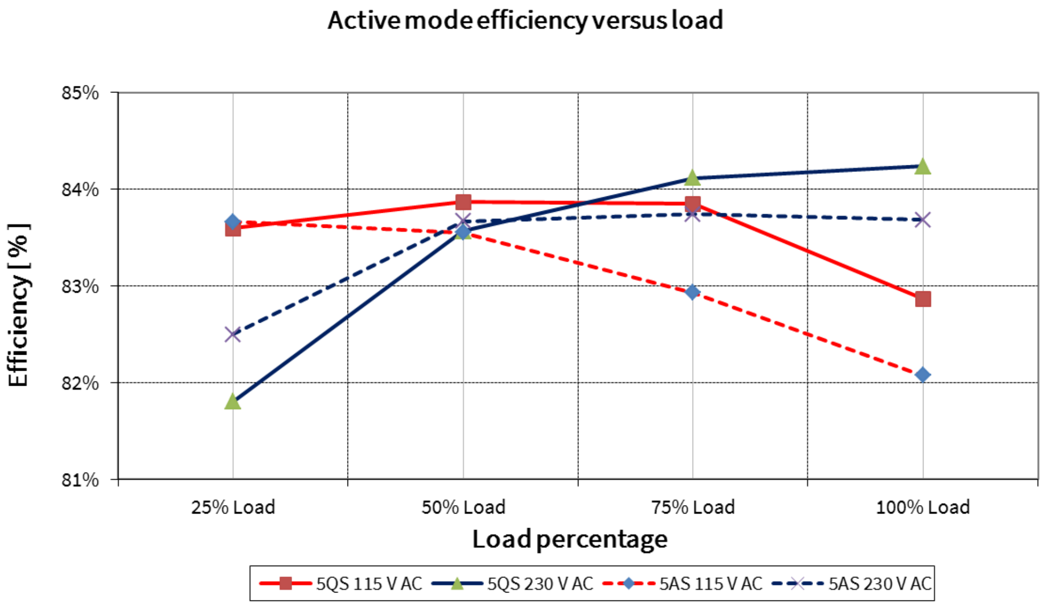


Figure 15 115 V AC and 230 V AC efficiency

3.3.3 Maximum input power before over-load

The maximum input power of FF DCM has a smaller tolerance with respect to AC-line compared to QR because of its inherent FF switching added with propagation delay compensation PCL.

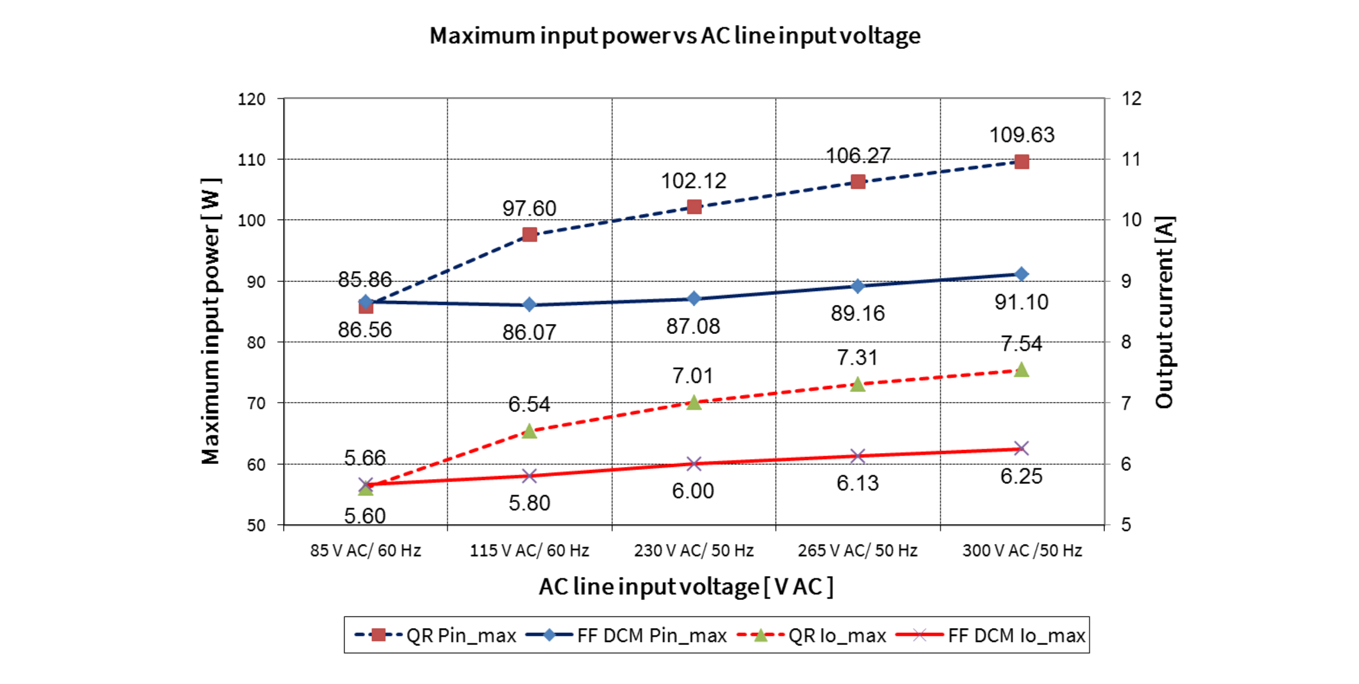


Figure 16 Maximum input power vs AC-line input voltage

3.4 Waveform and oscilloscope plots

3.4.1 Drain voltage and current

As can be seen in Figure 17, the drain peak current and switching frequency of both QR and FF DCM are equal. This makes the full-load efficiency of both QR and FF DCM almost equal at 85 V AC.

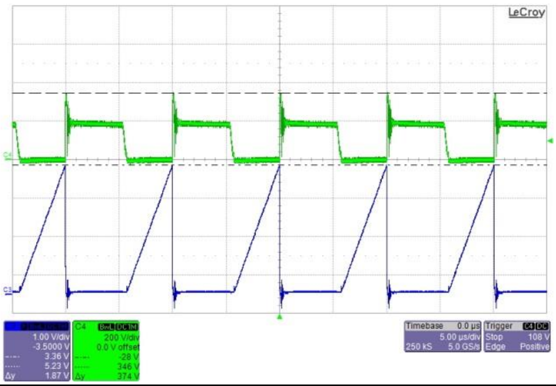
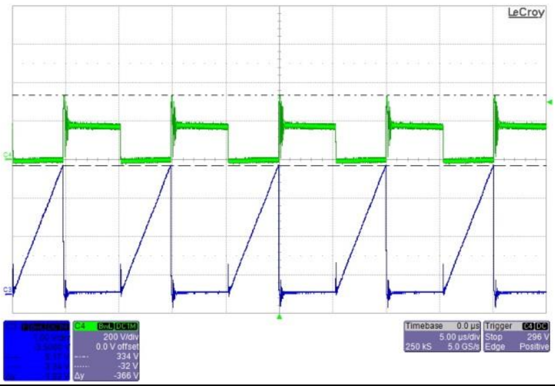
QR	**FF DCM**
	
C3 (blue) : Drain current C4 (green) : Drain voltage	C3 (blue) : Drain current C4 (green) : Drain voltage
3.36 A peak current switching at 100 kHz	3.34 A peak current switching at 100 kHz

Figure 17 Drain voltage and current waveform at 85 V AC full load

At higher input voltage, the QR switching frequency is higher. Therefore, the drain peak current is lower, resulting in lower conduction loss. Although the switching loss is higher with higher switching frequency, conduction loss dominates, especially at high peak currents. This makes the full-load efficiency of QR higher compare to FF DCM at 300 V AC.

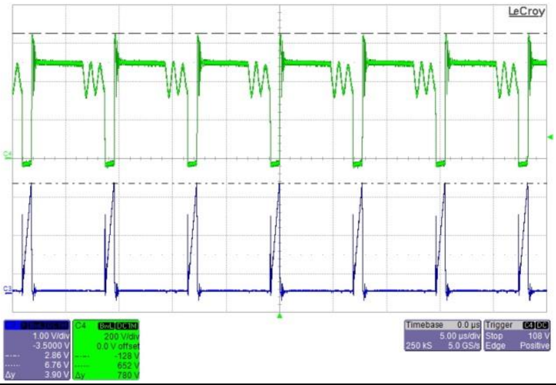
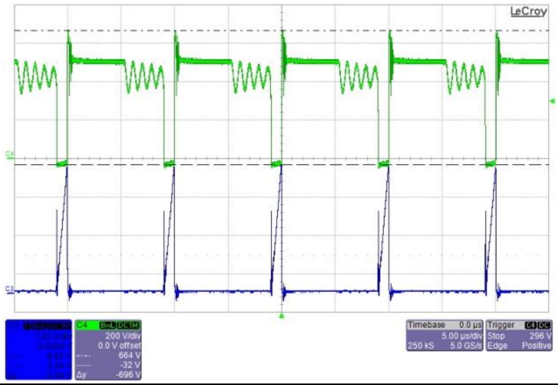
QR	FF DCM
	
C3 (blue) : Drain current C4 (green) : Drain voltage	C3 (blue) : Drain current C4 (green) : Drain voltage
2.86 A peak current switching at 130 kHz	3.34 A peak current switching at 100 kHz

Figure 18 Drain voltage and current waveform at 300 V AC full load

3.4.2 Output ripple voltage

The switching frequency of QR is dependent on the input voltage. Therefore, the output voltage ripple of QR has a higher AC component ripple than FF DCM. The output voltage ripple is more evident at low input voltage where the change of switching frequency is high due to large bus voltage ripple.

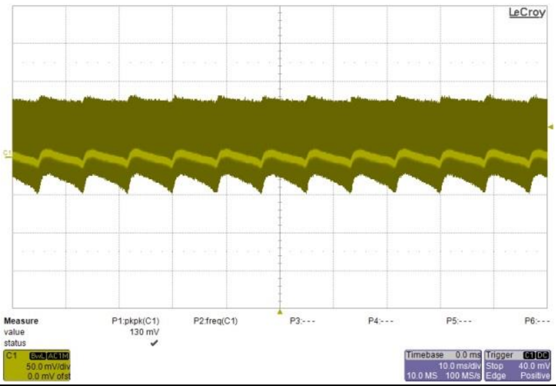
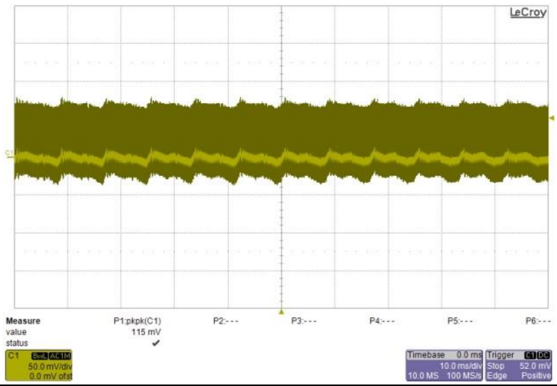
QR	FF DCM
	
130 mV peak-to-peak ripple voltage	115 mV peak-to-peak ripple voltage

Figure 19 Output voltage ripple at 85 V AC full load. Probe terminals are decoupled with 1 µF electrolytic and 0.1 µF ceramic capacitors. Oscilloscope is bandwidth filter limited to 20 MHz.

At high input voltage, the AC component ripple of QR is negligible, as the change in switching frequency is very small due to low bus voltage ripple. There is a small 250 Hz voltage ripple on FF DCM due to the in-built frequency jittering.

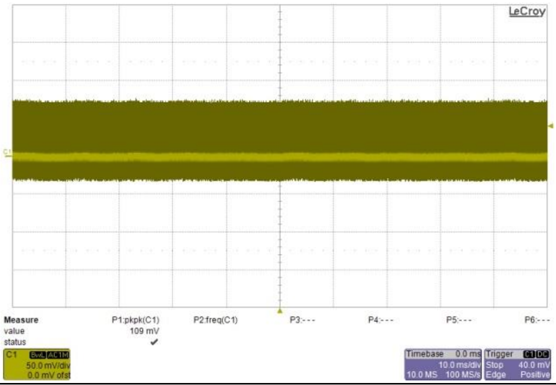
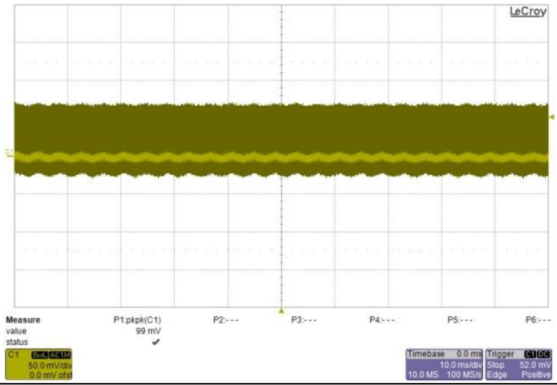
QR	FF DCM
	
109 mV peak-to-peak ripple voltage	99 mV peak-to-peak ripple voltage

Figure 20 Output voltage ripple at 300 V AC full load. Probe terminals are decoupled with 1 µF electrolytic and 0.1 µF ceramic capacitors. Oscilloscope is bandwidth filter limited to 20 MHz.

3.5 Thermal measurement

There is no big difference (less than ±4°C) between the power component temperature of QR and FF DCM.

Table 6 Thermal measurement in open case under 25°C ambient temperature

	85 V AC				300 V AC			
	Controller	MOSFET	Transformer	Output diode	Controller	MOSFET	Transformer	Output diode
QR	102.0	70.7	84.0	98.2	61.9	68.8	93.1	95.3
FF DCM	99.7	73.0	81.3	94.7	63.7	68.4	90.6	95.0

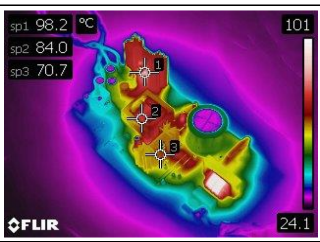
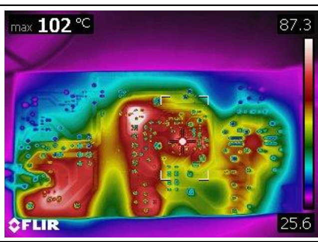
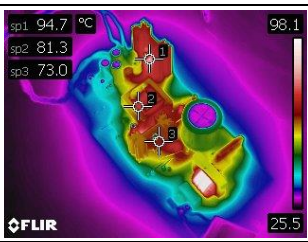
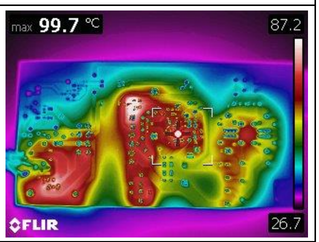
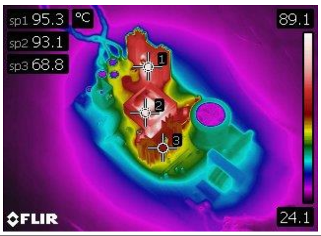
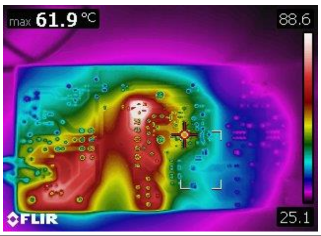
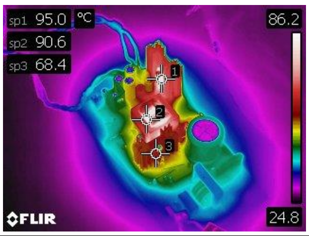
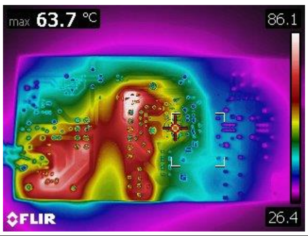
	QR		FF DCM	
	Top	Bottom	Top	Bottom
85 V AC				
300 V AC				

Figure 21 Thermal images in open case under 25°C ambient temperature

3.6 EMI measurement

Table 7 Quasi-peak margin measurement

	115 V AC		230 V AC	
	Line	**Neutral**	**Line**	**Neutral**
QR	9.4 dB at 9.8 MHz	9.9 dB at 8.9 MHz	6 dB at 10.1 MHz	8.7 dB at 9.1 MHz
FF DCM	7.8 dB at 0.2 MHz	7.3 dB at 0.2 MHz	9.1 dB at 29.9 MHz	9.1 dB at 29.9 MHz

At 115 V AC, the full-load switching frequency of QR is 130 kHz while FF DCM is 100 kHz. Therefore, they have different EMI data at a low frequency band (less than 1 MHz). At higher frequency (1 to 30 MHz), both QR and FF DCM have the same EMI curve, but the FF DCM is lower by around 3 dB. Overall, both QR and FF DCM have enough margin.

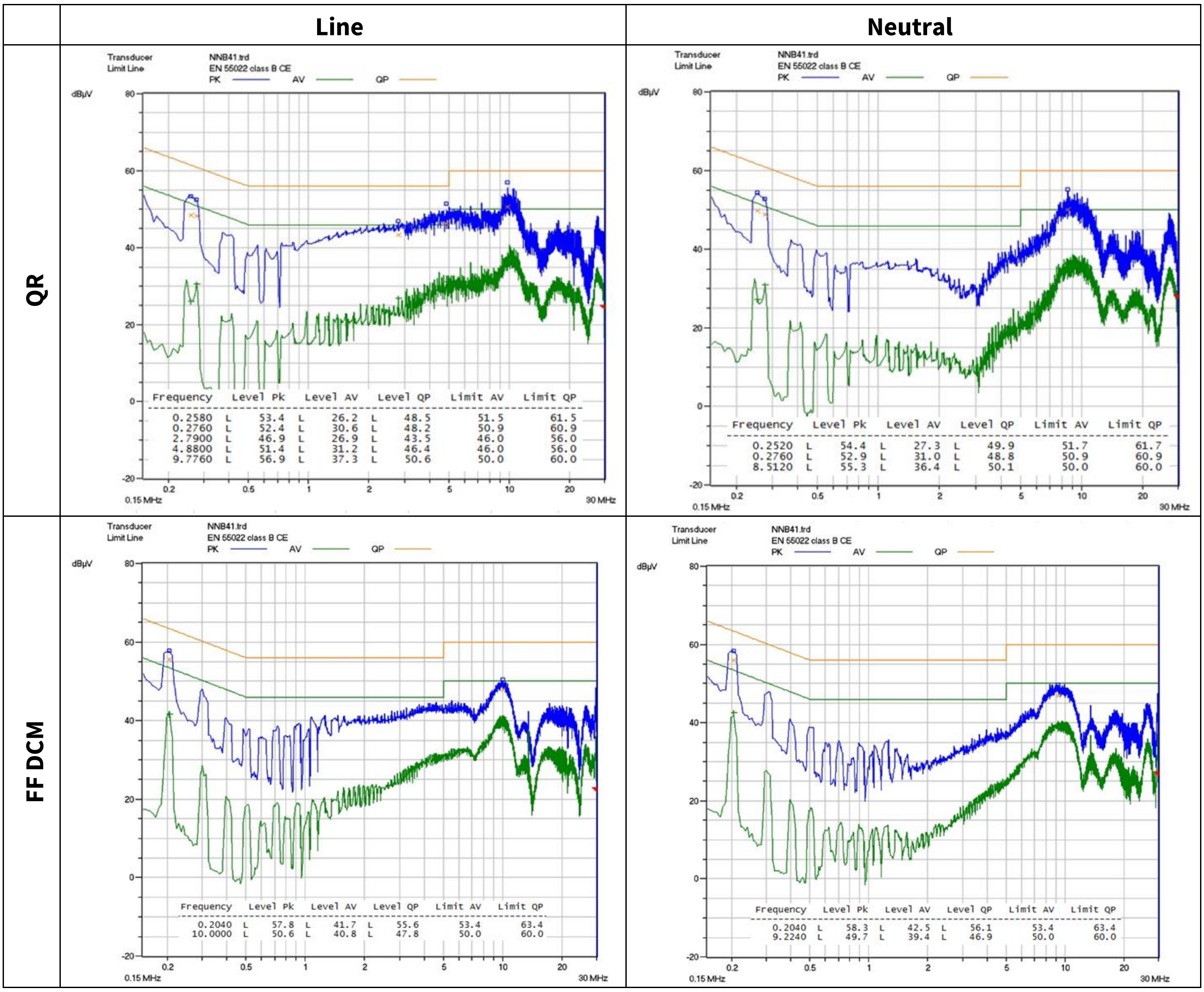


Figure 22 EMI scan at 115 V AC

At 230 V AC, it can be seen that the FF DCM has lower peaks on average due to the in-built frequency jittering. QR relies on bus voltage ripple for the jittering effect for a lower average. However, the small bus voltage ripple at high-line produces a very small jittering effect, and that is why the average peaks of QR are high at 230 V AC.

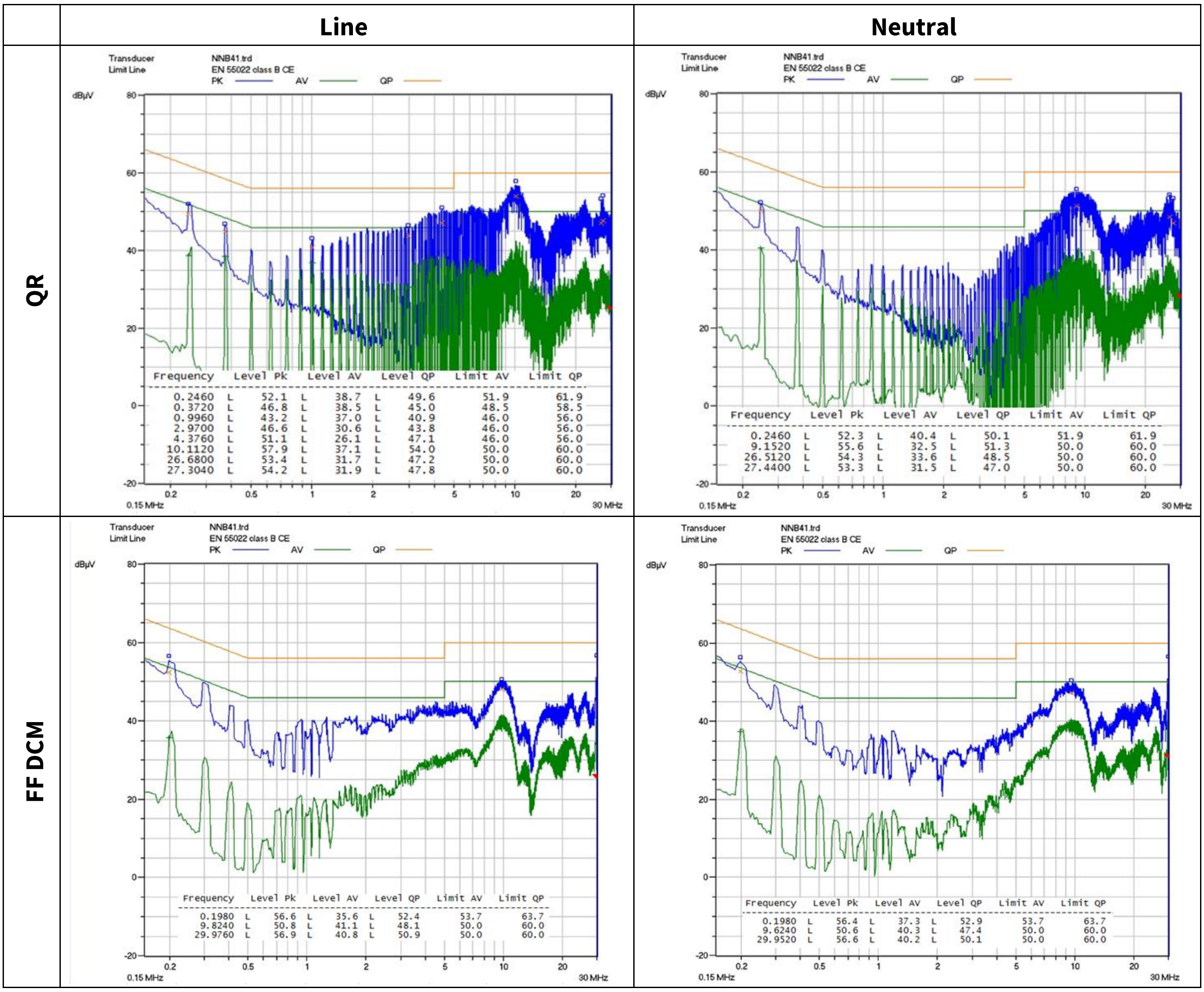


Figure 23 EMI scan at 230 V AC

4 QR and FF CCM comparison

4.1 Test condition and set-up

The transformer is redesigned so that at 85 V AC full load, the FF CCM will have a KRF of 0.4 with 100 kHz switching frequency. With the same transformer design, the QR switching frequency is 40 kHz. Therefore, the same transformer is used in the evaluation of both QR and FF CCM. The transformer core used is ER28/17 TP4A with winding specification as shown in Figure 24. It is bigger compared to the transformer used in FF DCM due to the higher inductance requirement, which requires more turns and therefore a bigger winding area.

Core: ER28/17 TP4A

Primary inductance: 270 µH

Start	Stop	No. of turns	Wire size	Layer
4	5	22	4 x AWG#29	1/2 Primary
6		9	3 x AWG#27	Shield
8	10	7	1 x LITZ (120x38)	Secondary
6		9	3 x AWG#27	Shield
5	6	22	4 x AWG#29	1/2 Primary
1	2	9	1 x AWG#20	Auxiliary

Figure 24 QR and FF CCM transformer specification

Since ICE5QSAG and ICE5xSAG have different PCL threshold voltage V_{CS_N} levels, the CS resistors are also changed as shown in Table 8, so that the over-load power will be as close as possible.

Table 8 ICE5QSAG and ICE5ASAG V_{CS_N} and CS resistor (R14)

Controller	V_{CS_N}	CS resistor (R14)
ICE5QSAG	1.0 V	0.273 Ω
ICE5ASAG	0.8 V	0.319 Ω

4.2 Frequency curve

With the transformer design, the QR switching frequency is lower than the FF CCM on all load conditions, as shown in Figure 25. This results in lower switching losses.

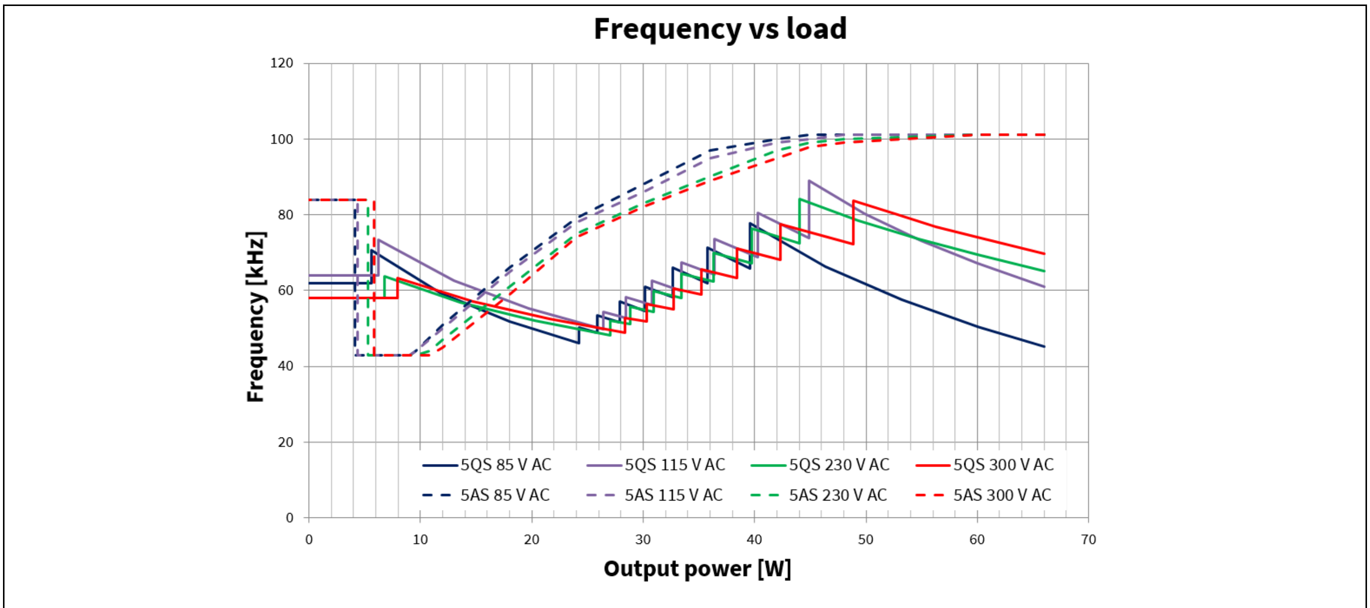


Figure 25 Frequency vs output load

4.3 Electrical test measurement

The input power is measured using WT210 power meter integration function. The sequence of measurement is from full load down to no load, which will make the QR operate at a higher switching frequency.

4.3.1 Electrical test measurement

Table 9 Electrical measurement based on QR controller (ICE5QSAG with 40 kHz transformer design)

Input (V AC/ Hz)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	Efficiency (percent)	Average efficiency (percent)	OLP P_{IN} (W)	OLP I_{OUT} (A)
85 V AC/ 60 Hz	0.05560	12.0649	0.0000				87.46	5.74
	7.334	12.0639	0.5000	6.03	82.24%			
	17.920	12.0618	1.2506	15.08	84.18%	82.51%		
	36.273	12.0581	2.5018	30.17	83.17%			
	54.878	12.0548	3.7531	45.24	82.44%			
	75.114	12.0514	5.0031	60.29	80.27%			
115 V AC/ 60 Hz	0.05954	12.0646	0.0000				99.86	6.73
	7.167	12.0630	0.5000	6.03	84.16%			
	17.773	12.0613	1.2506	15.08	84.87%	84.42%		
	35.622	12.0578	2.5018	30.17	84.68%			
	53.450	12.0544	3.7531	45.24	84.64%			
	72.234	12.0509	5.0031	60.29	83.47%			
230 V AC/ 50 Hz	0.08908	12.0642	0.0000				107.77	7.48
	7.330	12.0626	0.5000	6.03	82.29%			
	17.997	12.0611	1.2506	15.08	83.81%	84.98%		
	35.396	12.0577	2.5018	30.17	85.22%			
	52.894	12.0544	3.7531	45.24	85.53%			
	70.632	12.0511	5.0031	60.29	85.36%			
265 V AC/ 50 Hz	0.10319	12.0643	0.0000				110.68	7.70
	7.400	12.0626	0.5000	6.03	81.51%			
	18.157	12.0611	1.2506	15.08	83.07%	84.65%		
	35.536	12.0576	2.5018	30.17	84.89%			
	53.044	12.0543	3.7531	45.24	85.29%			
	70.656	12.0509	5.0031	60.29	85.33%			
300 V AC/ 50 Hz	0.12277	12.0627	0.0000				113.60	7.91
	7.467	12.0623	0.5000	6.03	80.77%			
	18.325	12.0610	1.2506	15.08	82.31%	84.26%		
	35.680	12.0574	2.5018	30.17	84.54%			
	53.235	12.0542	3.7531	45.24	84.98%			
	70.758	12.0509	5.0031	60.29	85.21%			

QR and FF CCM comparison

Table 10 Electrical measurement based on FF controller (ICE5ASAG) in CCM

Input (V AC/ Hz)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	Efficiency (percent)	Average efficiency (percent)	OLP P_{IN} (W)	OLP I_{OUT} (A)
85 V AC/ 60 Hz	0.06455	12.0659	0.0000				87.35	5.77
	7.285	12.0643	0.5000	6.03	82.80%			
	17.936	12.0623	1.2506	15.09	84.10%	82.64%		
	36.114	12.0591	2.5018	30.17	83.54%			
	54.952	12.0551	3.7531	45.24	82.33%			
	74.814	12.0515	5.0031	60.29	80.59%			
115 V AC/ 60 Hz	0.06821	12.0659	0.0000				94.82	6.44
	7.292	12.0643	0.5000	6.03	82.72%			
	17.824	12.0622	1.2506	15.08	84.63%	84.13%		
	35.668	12.0588	2.5018	30.17	84.58%			
	53.795	12.0559	3.7531	45.25	84.11%			
	72.462	12.0518	5.0031	60.30	83.21%			
230 V AC/ 50 Hz	0.09889	12.0655	0.0000				103.56	7.20
	7.544	12.0636	0.5000	6.03	79.95%			
	18.034	12.0615	1.2506	15.08	83.64%	84.81%		
	35.602	12.0581	2.5018	30.17	84.73%			
	52.939	12.0548	3.7531	45.24	85.46%			
	70.602	12.0513	5.0031	60.29	85.40%			
265 V AC/ 50 Hz	0.11411	12.0656	0.0000				105.04	7.30
	7.656	12.0635	0.5000	6.03	78.78%			
	18.202	12.0615	1.2506	15.08	82.87%	84.31%		
	35.789	12.0583	2.5018	30.17	84.29%			
	53.376	12.0550	3.7531	45.24	84.76%			
	70.686	12.0518	5.0031	60.30	85.30%			
300 V AC/ 50 Hz	0.13349	12.0656	0.0000				106.41	7.38
	7.799	12.0630	0.5000	6.03	77.33%			
	18.275	12.0606	1.2506	15.08	82.53%	83.68%		
	36.128	12.0572	2.5018	30.16	83.49%			
	53.903	12.0535	3.7531	45.24	83.93%			
	71.130	12.0502	5.0031	60.29	84.76%			

4.3.2 Efficiency curve

The full-load efficiency of FF CCM is higher at 85 V AC by up to 0.3 percent due to the lower RMS current, as shown in Figure 26. However, the average efficiency of QR is higher than FF CCM due to its lower switching frequency throughout the input line range (up to 0.17 percent at 230 V AC).

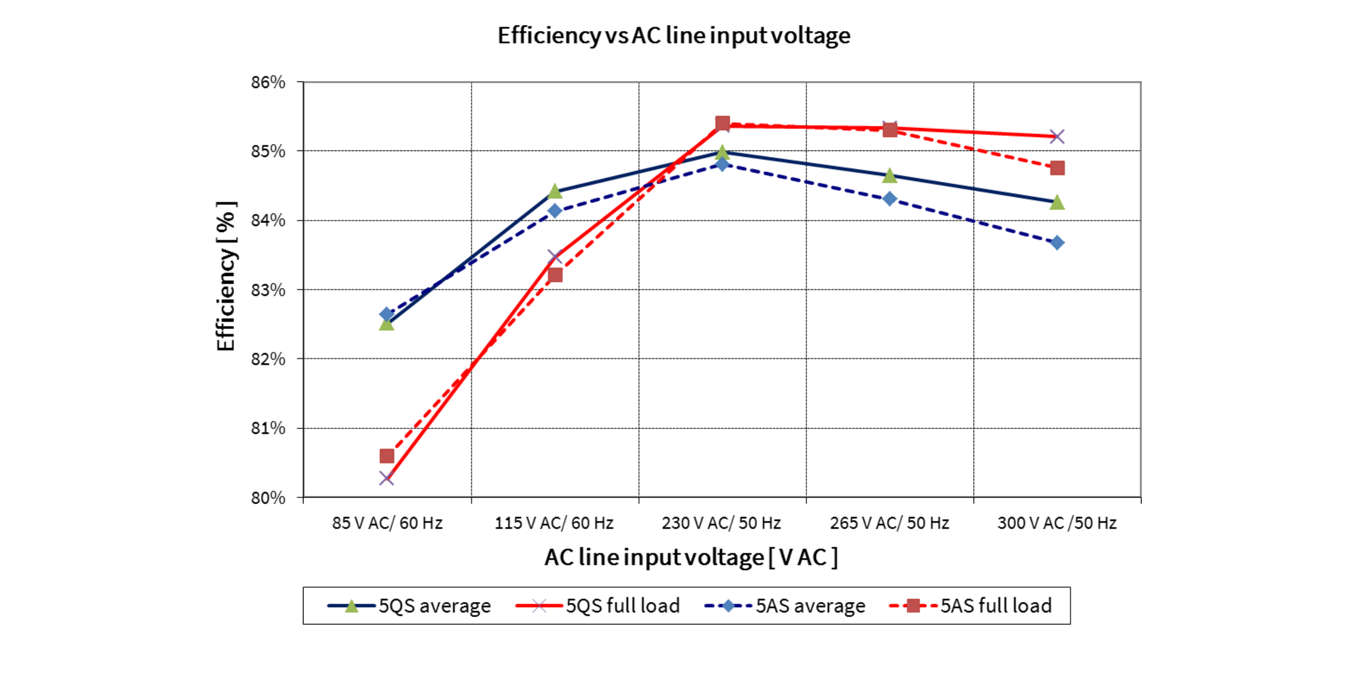


Figure 26 Average and full-load efficiency

The QR efficiency is higher than FF CCM due to lower switching frequency at nominal line input voltages, as show in Figure 27.

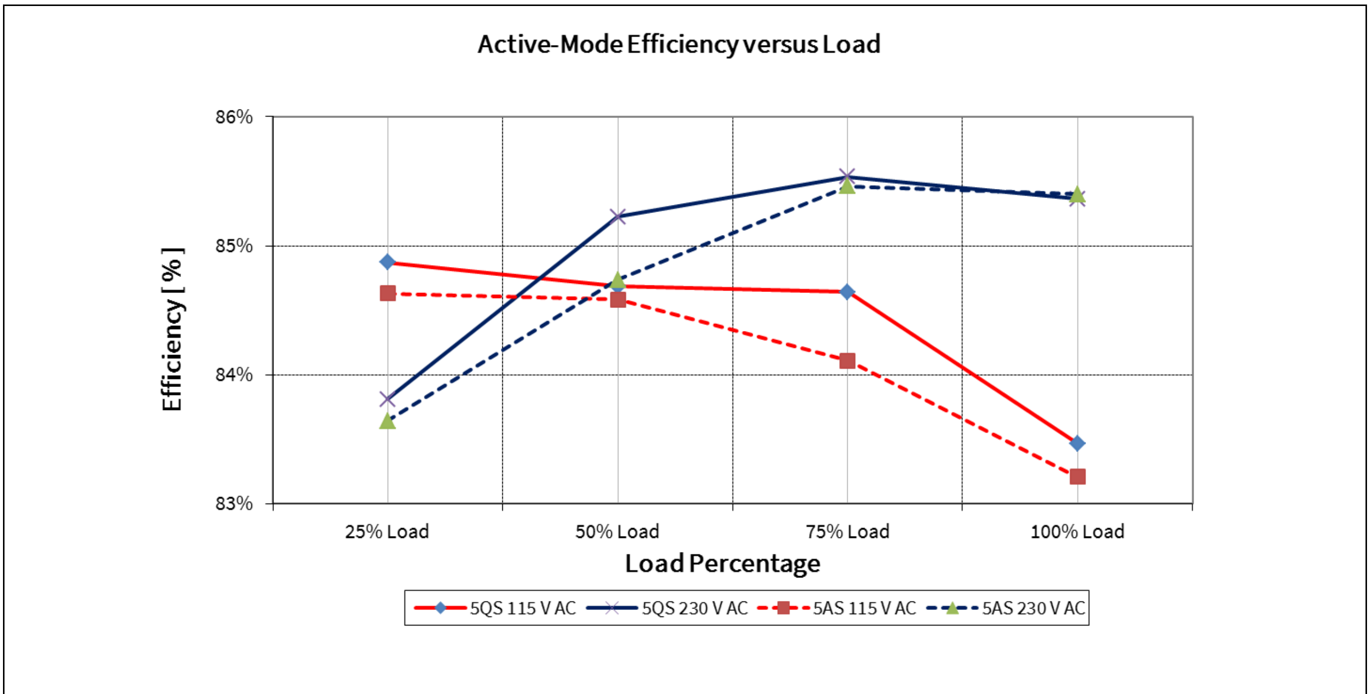


Figure 27 115 V AC and 230 V AC efficiency

4.3.3 Maximum input power before over-load

The overall maximum input power of FF CCM has a smaller tolerance with respect to AC-line compared to QR. With CCM operation itself, which is at low-line, the tolerance is not good, as can be seen from 85 V AC to 230 V AC. However, the operation becomes DCM at high-line and the tolerance is improved, as can be seen from 230 V AC to 300 V AC.

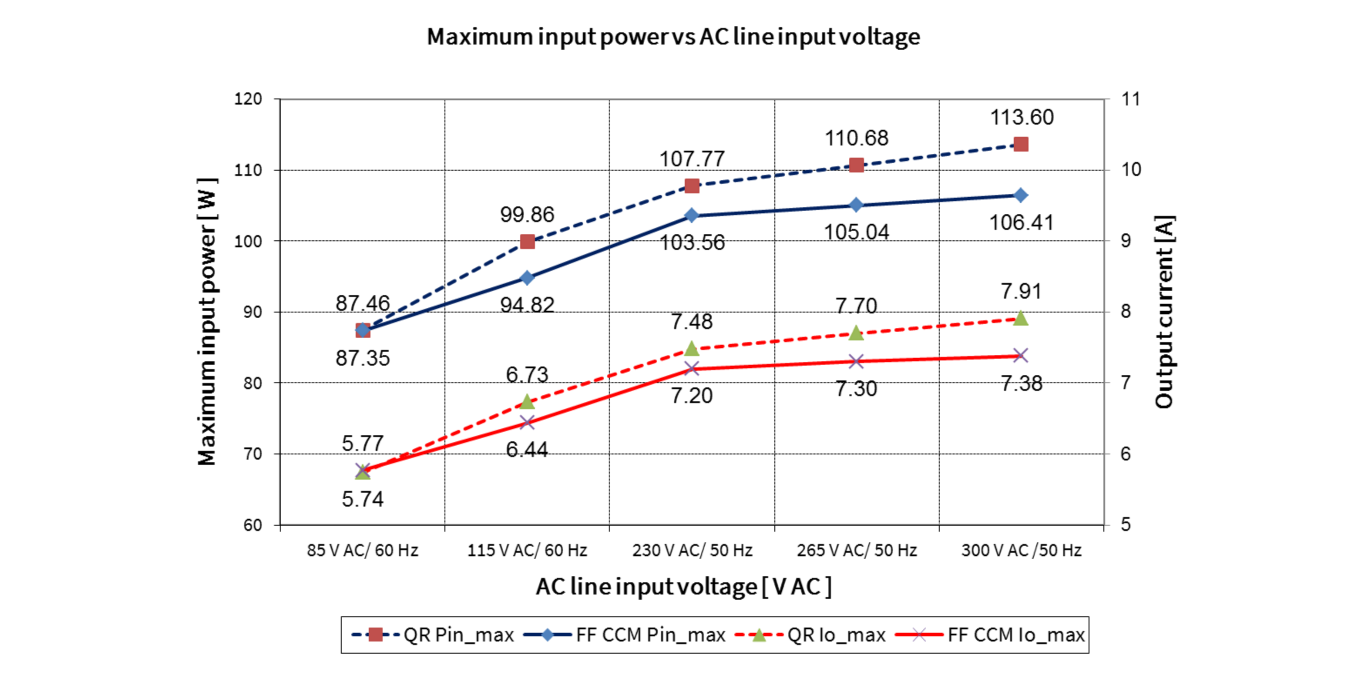


Figure 28 Maximum input power vs AC-line input voltage

4.4 Waveform and oscilloscope plots

4.4.1 Drain voltage and current

The RMS current of QR is higher than FF CCM. Therefore, the conduction loss of QR is higher, especially at low input voltage. Although the switching frequency of QR (50 kHz) is only half of FF CCM (100 kHz), the switching loss is not dominant at low input AC-line. This makes the FF CCM full-load efficiency higher than QR at 85 V AC.

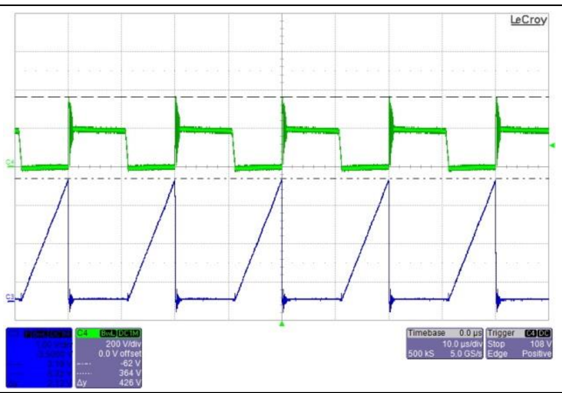
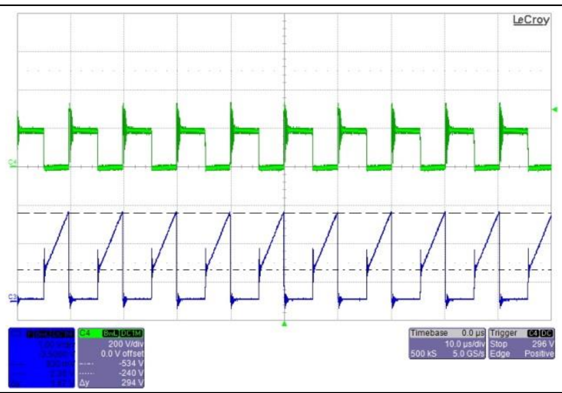
QR	FF CCM
	
C3 (blue) : Drain current C4 (green) : Drain voltage	C3 (blue) : Drain current C4 (green) : Drain voltage
3.19 A peak current switching at 50 kHz	2.3 A peak current switching at 100 kHz

Figure 29 Drain voltage and current waveform at 85 V AC full load

At higher input voltage, the QR switching frequency is lower. Therefore, the drain peak current is higher resulting in higher conduction loss. Although the conduction loss is higher with lower switching frequency, switching loss dominates at lower peak currents and high input AC-line. This makes the full-load efficiency of QR higher compared to FF CCM at 300 V AC.

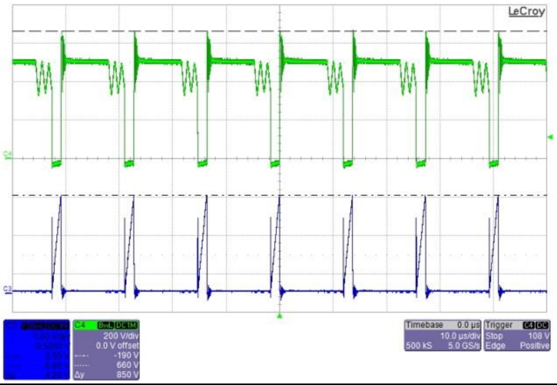
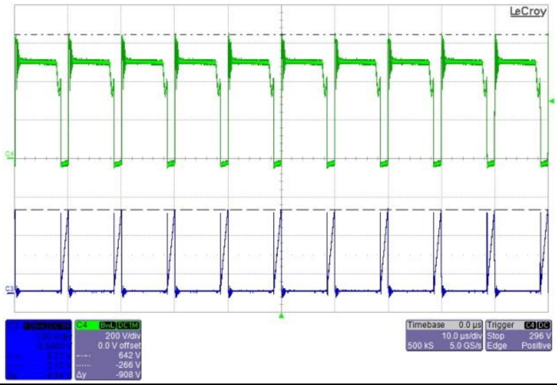
QR	FF CCM
	
C3 (blue) : Drain current C4 (green) : Drain voltage	C3 (blue) : Drain current C4 (green) : Drain voltage
2.55 A peak current switching at 74 kHz	2.17 A peak current switching at 100 kHz

Figure 30 Drain voltage and current waveform at 300 V AC full load

4.4.2 Output ripple voltage

The switching frequency of QR is dependent on the input voltage. Therefore, the output voltage ripple of QR has a higher AC component ripple than FF CCM. The output voltage ripple is more evident at low input voltage where the change of switching frequency is high due to large bus voltage ripple.

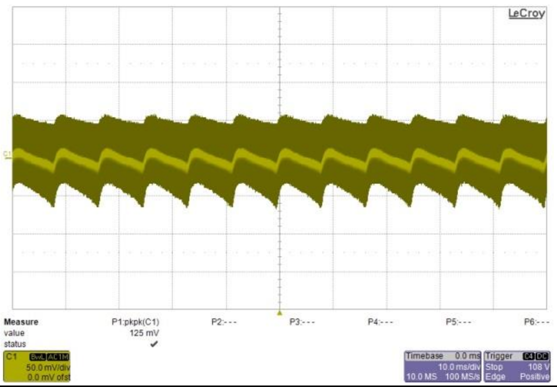
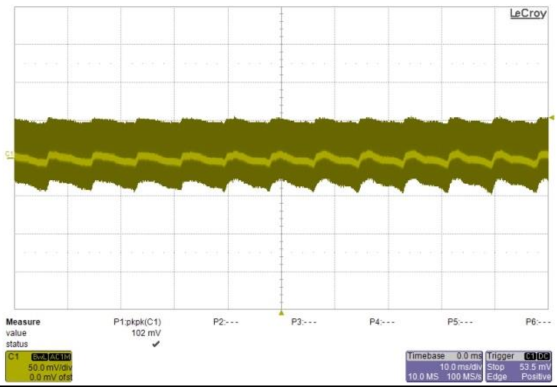
QR	FF CCM
	
125 mV peak-to-peak ripple voltage	102 mV peak-to-peak ripple voltage

Figure 31 Output voltage ripple at 85 V AC full load. Probe terminals are decoupled with 1 µF electrolytic and 0.1 µF ceramic capacitors. Oscilloscope is bandwidth filter limited to 20 MHz.

At high input voltage, the AC component ripple of QR is negligible as the change in switching frequency is very small due to low bus voltage ripple. There is a small 250 Hz voltage ripple on FF DCM due to the in-built frequency jittering.

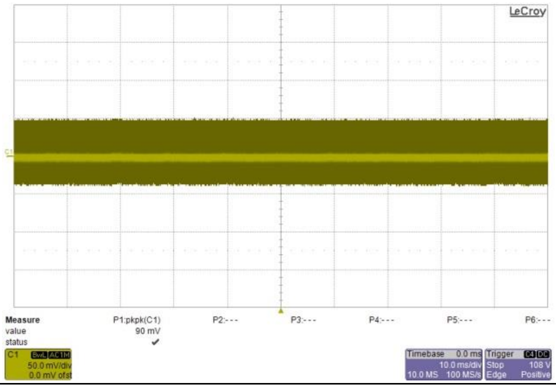
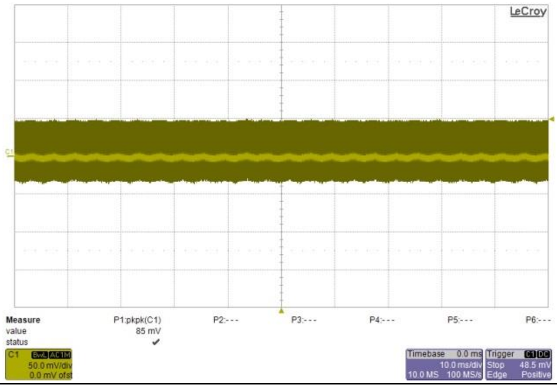
QR	**FF CCM**
	
90 mV peak-to-peak ripple voltage	85 mV peak-to-peak ripple voltage

Figure 32 Output voltage ripple at 300 V AC full load. Probe terminals are decoupled with 1 µF electrolytic and 0.1 µF ceramic capacitors. Oscilloscope is bandwidth filter limited to 20 MHz.

4.5 Thermal measurement

The QR controller temperature at 85 V AC is hotter by 10°C because of higher RMS current flowing through the low-side MOSFET inside the controller. The FF CCM MOSFET temperature at 300 V AC is hotter by 10°C because of higher switching loss due to higher switching frequency.

Table 11 Thermal measurement in open case under 25°C ambient temperature

	85 V AC				**300 V AC**			
	Controller	MOSFET	Transformer	Output diode	Controller	MOSFET	Transformer	Output diode
QR	97.8	64.1	78.0	95.4	57.5	56.3	85.6	93.8
FF CCM	87.2	64.2	78.0	95.5	60.7	66.2	87.4	90.9

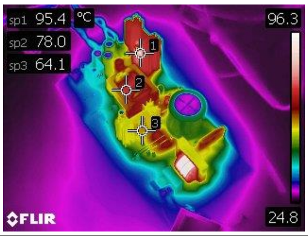
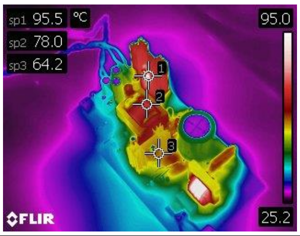
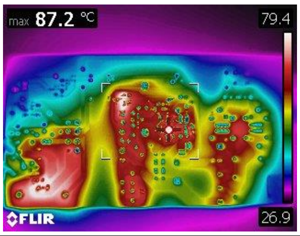
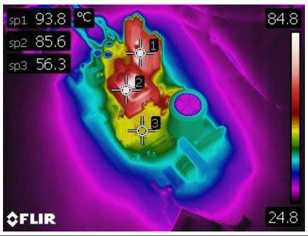
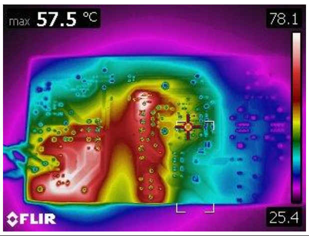
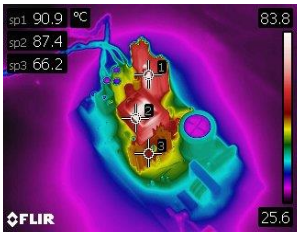
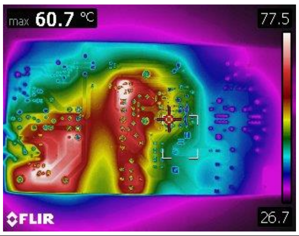
	QR		**FF CCM**	
	Top	Bottom	Top	Bottom
85 V AC				
300 V AC				

Figure 33 Thermal images in open case under 25°C ambient temperature

4.6 EMI measurement

Table 12 Quasi-peak margin measurement

	115 V AC		230 V AC	
	Line	**Neutral**	**Line**	**Neutral**
QR	11.9 dB at 2.67 MHz	More than 12 dB	9.2 dB at 2.64 MHz	10.3 dB at 0.2 MHz
FF CCM	-2.1 dB at 29.9 MHz (fail)	0.4 dB at 29.8 MHz	-2.1 dB at 29.9 MHz (fail)	-1.4 dB at 29.9 MHz (fail)

At 115 V AC, the 200 kHz EMI for QR is lower as it is the third harmonic while it is the second harmonic for FF CCM. Starting from 3 MHz, FF CCM and QR have a different EMI curve. At around 29 MHz, FF CCM is failing by 2 dB on quasi-peak and average.

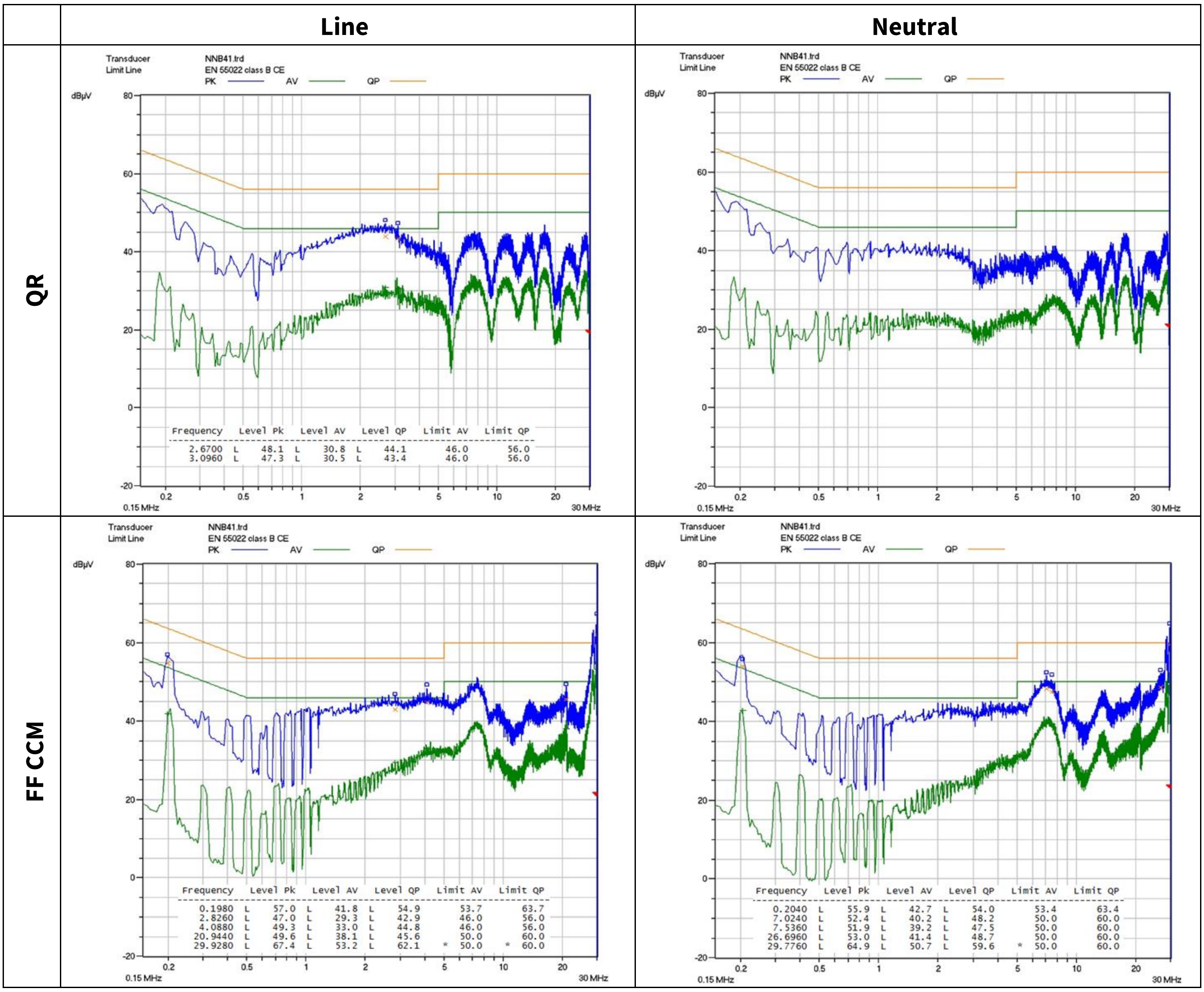


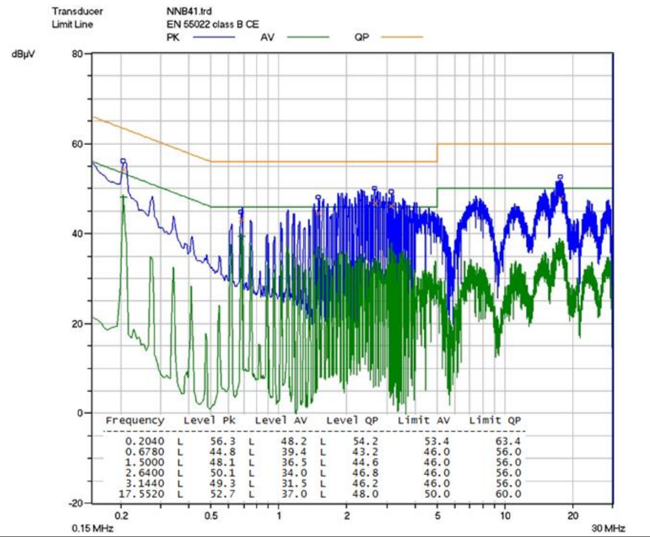
Figure 34 EMI scan at 115 V AC

At 230 V AC, the 200 kHz EMI for QR is lower as it is the third harmonic while it is the second harmonic for FF CCM. Starting from 5 MHz, FF CCM and QR have a different EMI curve. At around 29 MHz, FF CCM is failing by 2 dB on quasi-peak and average.

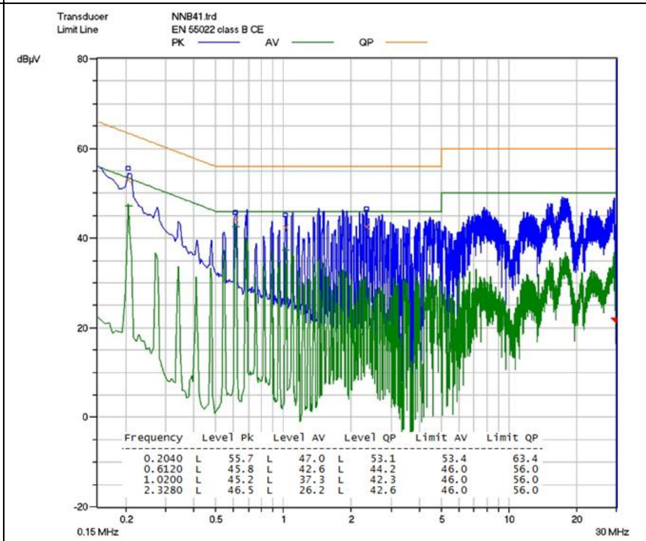
It can be seen that the FF CCM has lower peaks on average due to the in-built frequency jittering. QR relies on bus voltage ripple for the jittering effect for a lower average. However, the small bus voltage ripple at high-line produces a very small jittering effect, and that is why the average peaks of QR are high at 230 V AC.

	Line	**Neutral**

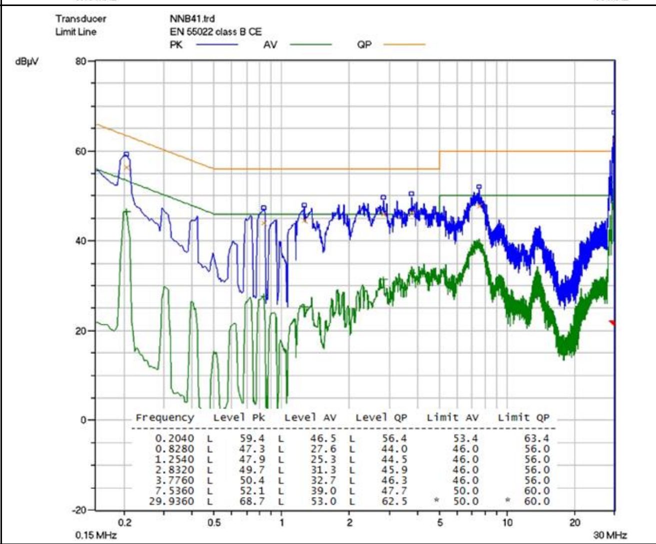
QR – Line



QR – Neutral



FF DCM – Line



FF DCM – Neutral

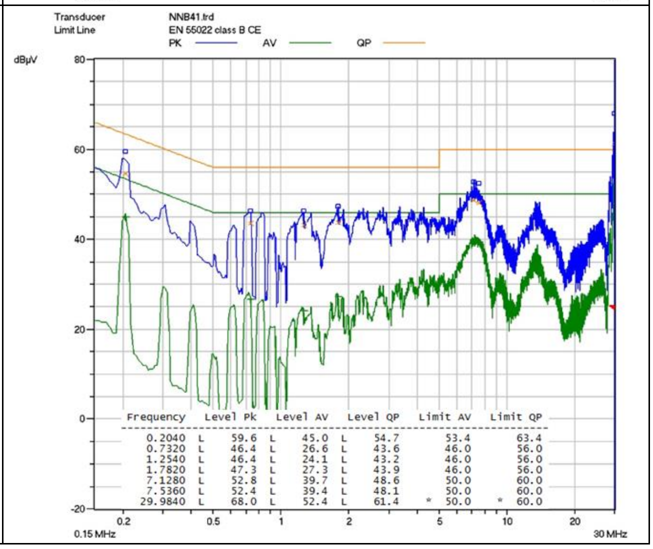


Figure 35 EMI scan at 230 V AC

5 Summary

From the evaluation of the 60 W demo board, the results show each switching scheme's advantages and disadvantages. Across line and load range, the efficiency of QR is favorable compared to FF. However, FF has the advantage of lower output voltage ripple and more controlled maximum output power over AC-line. FF CCM has thermal advantages at worst-case minimum AC-line input.

The most suitable switching scheme for the designer to use depends on various factors, such as the electrical specifications (e.g. input voltage range, output power, etc.), meeting efficiency standards (e.g. Energy Star, California Energy Commission, 80 Plus, etc.), development time and many more. Therefore, the designer should understand each flyback switching scheme's advantages and disadvantages. This application note serves only as a guide to help designers in the selection of flyback switching scheme.

There are other flyback switching scheme options that designers may choose, such as Pulse Frequency Modulation (PFM) control. Other controllers operate in multi-mode, wherein the switching scheme varies between QR, FF or PFM depending on a certain condition, such as load condition.

In the end, the right selection will benefit the designer in many ways, such as achieving and meeting the specifications more quickly and easily, shorter development time and much more.

6 References

[1] ICE5xSAG datasheet, Infineon Technologies AG

[2] ICE5QSAG datasheet, Infineon Technologies AG

[3] DEMO_5QSAG_60W1 application note, Infineon Technologies AG

Revision history

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