SiC Cascode in 440 VAC - 800 VDC Power Factor Correction

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Abstract

Until recently, the selection for switching devices in 440 VAC applications has been rather limited. The choice was typically between an IGBT or a large, high gate capacitance MOSFET. This power switch selection tended to limit switching frequencies to less than 50 kHz., which then required larger, more expensive inductors to maintain good power factor. With the introduction of wide bandgap switching devices, good efficiencies at higher switching frequencies become attainable, while producing more cost effective solutions by lowering the required inductance. This paper will explore the design tradeoffs for efficiency and power factor in implementing designs at higher frequencies (>75 kHz). For simplicity, only a single phase will be analyzed.

1.0 Power Factor Correction

This paper will focus on hard switched PFC's, as shown in their simplified form in Figure 1. The current through the boost inductor is PWM'd to mirror the input Voltage (Figure 2). This process makes the converter appear as a resistive load (PFC=1), and thus reducing line harmonics, which is the goal of this power stage. It is therefore important that when evaluating PFC's, one must always consider Power Factor in the context of efficiency.

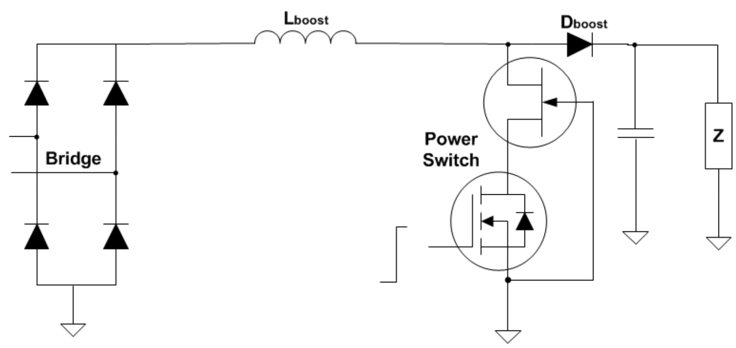

Figure 1: Basic Power Factor Correction Topology

Efficiency and Power Factor Correction

The common elements between Power Factor, efficiency and switching frequency are the power switch/boost diode pair and the inductor. An increase in frequency lowers the required inductance, which produces a smaller, cheaper inductor. The tradeoff with this is the obvious drop in efficiency due to the increased number of cycles. The goal is to find the correct tradeoff that generates the optimum power factor and efficiency at the right cost point.

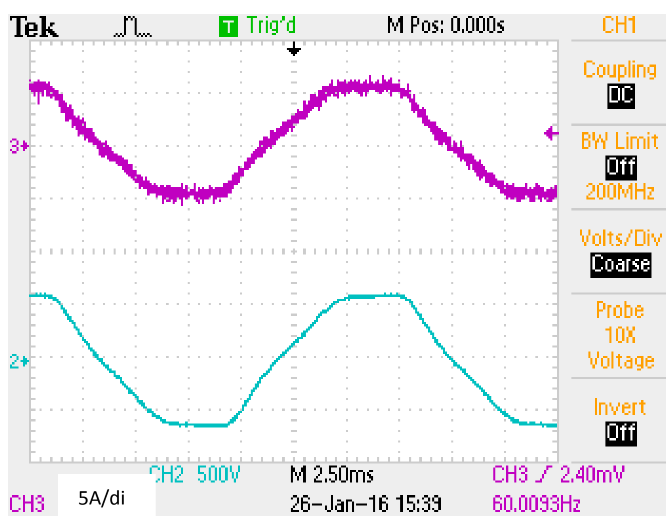

Figure 2: Vin = 440VAC, Iin = 3.8A, PF = 0.993, fs = 100 kHz

2.0 Boost Inductor

Equation 1 is the required boost inductance for continuous current mode (CCM) operation in a power factor correction converter. Figure 3 is the plot of this inductance with respect to switching frequency for a 440VAC input and an output power of 1.65kW. The inductor ripple current is set at 20% of the peak current (Note: There are many resources on the web with respect to PFC design, this paper will primarily rely on TI's UCC3818 datasheet, as it is PWM controller used in the test board).

1) $$Lboost(fs) := \frac{Vin \cdot \sqrt{2} \cdot D}{dI \cdot fs}$$

From the graph, the inductance can swing from 5.1 mH to 0.86 mH depending on frequency. The inductance value with respect to current required for the application will have a direct relationship to the cost of the inductor.

As an example, using the Magnetics Inc. software, and standardizing on the 55438 MPP core, a 25 kHz design, a 5.6 mH inductor requires 3 cores and 112 turns of 18 AWG, where a 150 kHz design, a 0.56 mH requires a single core 51 turns and there is room to use 14 AWG wire.

From a magnetics perspective it is clear that that moving to higher frequency / lower inductance one can produce a lower cost, more efficient inductor.

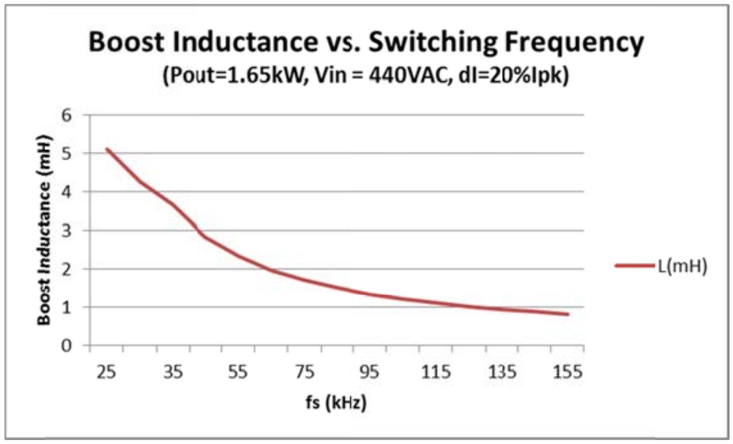

Figure 3: Boost Inductor vs. Switching Frequency

3.0 Switching Frequency

The inductance calculations highlight the advantages of increasing switching frequency, but the other side of the equation is that switching losses will be going up with frequency. A PFC test board (Figure 5) based on the UCC3818 current average controller was designed along the same criteria as the previous example: 440 to 480 VAC input, 800 VDC output with an output power of 1.65 kW(~ 5 kW in a three phase system). The initial design will be for a lower switching frequency converter, and then higher frequency will be investigated. Note: 1.65 kW was chosen as it still allows for stepping up 440 VAC from a standard 110 VAC line.

Figure 4: MPP Cores, 55438

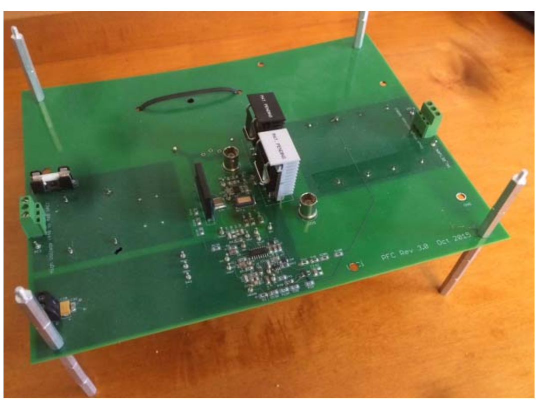

Figure 5: UCC3818 PFC Test Board

The Power Switch and Boost Diodes are the UJC1210K Cascode (1.2 kV, 100 mOhm max). The advantage of the UJC1210K is not only its fast switching capability, but that it can also be driven with standard gate drive. Its performance capability allows it to compete economically against silicon solutions. Note: all test results shown in this paper will use a V_{GS} drive of 0 to 14 Volts.

An USCi Silicon Carbide Diode, UJ2D1205T (1.2 kV, 5 A) with a Q_C of 14 nC will be the boost diode. Once the R_{G_L} and R_{G_H} are fixed, the only variables in the data will be the switching frequency, and the inductor design. A complete list of components can be found in the appendix. A Mathcad file based on Texas Instruments calculation is available upon request. This by no means a fully optimized design, but it is meant to highlight the relative tradeoffs between inductance and switching frequency with respect to efficiency and power factor.

4.0 Optimizing Gate Drive

As the UJC1210K is a cascode device, it is recommended to use the drive configuration shown in Figure 6. This allows control of the turn on and turn off behavior. As silicon carbide is inherently faster than silicon, and it is recommended to start with higher Rg values than silicon. In cascode, the R_{g_L} will typically be higher than the R_{g_H} value. It is recommended to start with an R_{g_H} of 10 Ohms and an R_{g_L} of 20 Ohms. These values can be swept +/- with selection determined by efficiency and EMI considerations.

In figure 7, such a process was undergone. A switching frequency of 130 kHz was chosen to accentuate the performance differences. An R_{g_H} at 7.5 Ohm and an R_{g_L} of 15 Ohms were determined to give acceptable results.

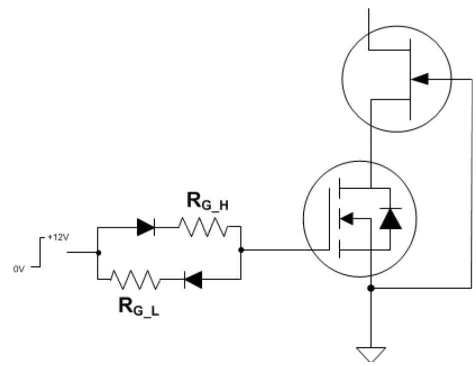

Figure 6: Cascode Rg_H and Rg_L Configuration

In Figure 8, the corresponding waveforms associated with these Rg values are shown. All waveforms appear well controlled with minimal ringing. An R_{g_H} of 7.5 Ohm and an R_{g_L} of 15 Ohms will be used in all measurements with the UJC1210K.

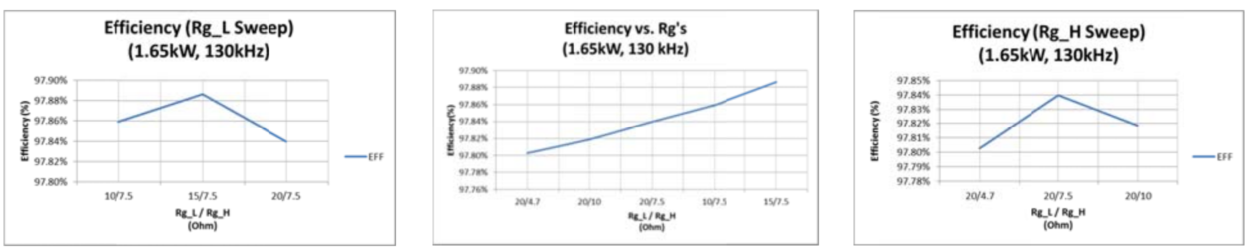

Figure 7: Rg_H and Rg_L Selection

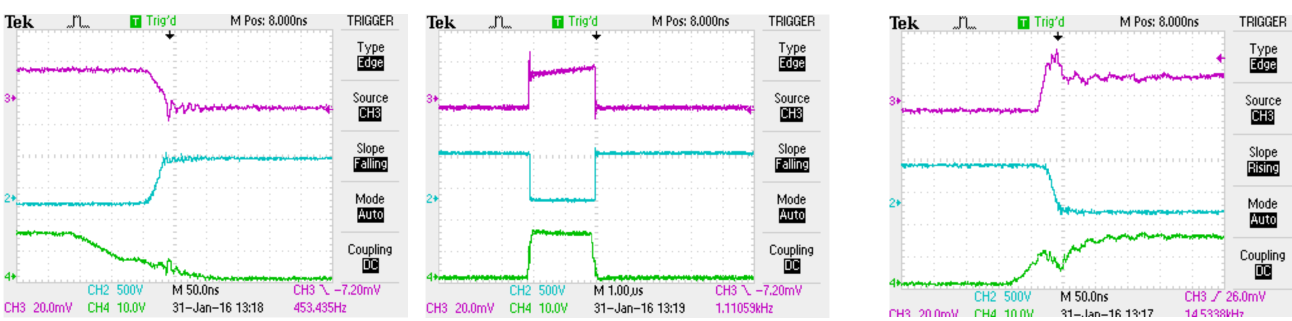

Figure 8: Turn Off, Full Period and Turn On (Rg_H=7.5 Ohm, Rg_L=15 Ohm)

5.0 Baseline Efficiency Curve

An Inductor was designed to generate good power factor down to switching frequency of 25 kHz. This curve will be used as a baseline to compare results against future optimizations, especially at higher frequencies. The inductor was wound using three 55438 MPP cores with 87 turns of 18 AWG, (3.9mH at the 1.65kW output power), which meets the criteria set in the graph of figure 1.

For measurement purposes, the input power and power factor are measured using a Tektronix PA 1000 Power Analyzer. The output power and 14V Controller/Driver Supply power are measured using Keysight 34465A 6.5 digit multi-meters. The lab power supply and the AC input power are added together for input power when calculating efficiency.

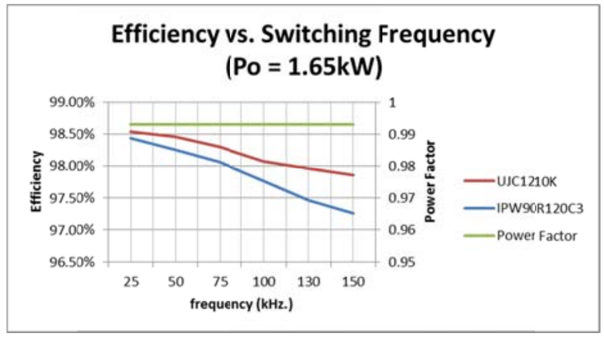

Figure 9: Efficiency vs. Switching Frequency

In figure 9 the UJC1210K efficiency curve is plotted with respect to switching frequency and power factor. As calculated, the power factor is well above 0.990 across all load and switching frequency conditions.

Per the data, the efficiency of the silicon carbide UJC1210K cascode (V_{GS}: 0 to 12 V) from 25 kHz to 150 kHz (98.55% @ 25 kHz / 97.87% @ 150 kHz) has a delta of 0.68%.

For a reference, this curve is compared against a similarly rated 900V super junction silicon MOSFET. The delta between efficiency across the same frequency spread is 1.19 percent. The efficiency delta grows between the two curves due switching losses as well as gate drive loss. A 6.9 Ohm gate resistor is used with the Silicon MOSFET, as compared to the 7.5 / 15 Ohm combination on the cascode.

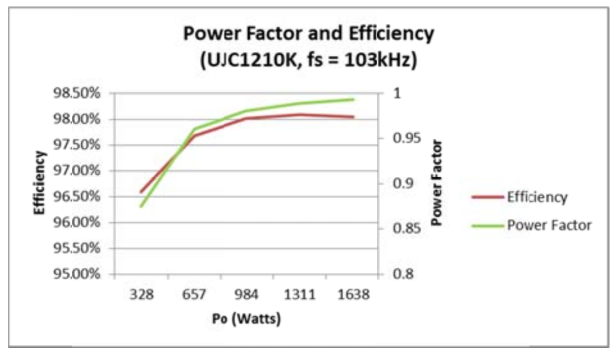

Figure 10: Efficiency vs. Load

Translating the efficiency comparison into actual loss, the cascode "loss delta" by increasing switching frequency from 25kHz to 150 kHz is 11.6 Watts, where the 900V, switching optimized MOSFET dissipates almost twice that amount at 20.3 Watts. By not dissipating the power in the first place, the SiC solution lowers the system thermal budget, and opens up the opportunity for higher switching frequency and lower inductor values.

In figure 10, the frequency is fixed at 103 kHz, and the load is swept from 328 Watts to 1.6 kW. It is noted that power factor with the given inductor begins to significantly roll off at 66% of load. The good news in this is that the peaks of the harmonics will also be dropping with power, so it is still possible to meet the line harmonic regulations with such a curve.

6.0 Lowering the Cost

In the previous example, the inductor was designed for low frequency operation (3.9 mH), and it still delivered reasonable results at 100 kHz and higher, but the goal in going to high frequency operation is to lower system cost with minimal impact to efficiency. A second inductor was designed to be optimized for 100 kHz operation, and only a single core (55438 MPP) is used. This design requires 68 turns of 14 AWG wire, to produce 1 mH inductance at load, which generates an inductor cost that is 30% of the previous example.

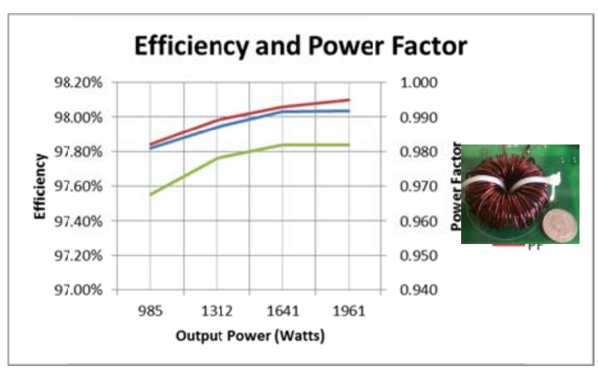

Figure 11: Boost Inductor (1 mH, 55438 MPP)

Per figure 11, the efficiency at 100 kHz exceeds 98% with an inductor 1/3 the size of the previous design. The power level is approaching 2 kW, which translates to 6 kW in a 3 phase system.

7.0 Conclusion

This design is not the final answer on how high the efficiency can be produced at 100 kHz. These examples are to illustrate that one can take a low frequency design with standard drive (0 to 14V), and by substituting a silicon carbide device (UJC1210K), and increasing the switching frequency >> 75 kHz, one can reduce the inductor cost down to 30% of a low frequency design and still produce efficiency performance in excess of 98% and power factor ≥ 99.0%

8.0 Parts List

Item	Designator	QTY	Value	Description	Manufacturer	Manufacturer #
1	C1, C8	2	220pF	CAP CER 220PF 50V NP0 1206	AVX Corporation	12065A221JAT2A
2	C36, C37, C5, C7	4	1UF	CAP CER 1UF 25V 10% X7R 1206	AVX Corporation	12063C105KAT2A
3	C38	1	47UF	CAP CER 47UF 25V 20% X5R 1206	TDK Corporation	C3216X5R1E476M160AC
4	C4	1	10000PF	CAP CER 10000PF 50V 10% X7R 1206	AVX Corporation	12065C103KAT2A
5	C6	1	3.9uF	C1206C395K3PACTU	KEMET	CGA5L1X7R1E685K160AC
6	C3, C39, C50, C42	4	0.1UF	CAP CER 0.1UF 50V 10% X7R 1206	AVX Corporation	12065C104KAT2A
9	C60, C11, C34, C35, C32, C33	6	0.15UF	CAP CER 0.15UF 1KV 10% X7R 2225	KEMET	C2225C154KDRACTU
10	C9	1	820pF	CAP CER 820PF 50V X7R 1206	Yageo	CC1206KRX7R9BB821
11	C12A, C12B,	2	50UF	CAP FILM 50UF 5% 900VDC RAD 4LD	Vishay	MKP1848C65090JY5
12	C15	1	2000PF	CAP CER 2000PF 50V NP0 1206	AVX Corporation	12065A202JAT2A
13	C20	1	47UF	CAP TANT 47UF 25V 10% 2917	AVX Corporation	TAJY476K025RNJ
14	C24, 25	2	1UF	CAP FILM 1UF 10% 1KVDC RADIAL	KEMET	R76QW4100SE30K
15	R1	1	27k	RES SMD 27K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT27K0
16	R8	1	20k	RES SMD 20K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT20K0
17	R5, R11, R9, R10	4	10K	RES SMD 10K OHM 1% 1/4W 1206	Panasonic	ERJ-8ENF1002V
18	R2A, R2B, R19A, R19B	4	249K	RES SMD 249K OHM 1% 1/4W 1206	Panasonic	ERJ-8ENF2493V
19	R3	1	9.31K	RES SMD 9.53K OHM 1% 1/4W 1206	Panasonic	ERJ-8ENF9311V
20	R4A, R4B, R20A, R20B	4	267K	RES SMD 267K OHM 1% 1/4W 1206	Panasonic	ERJ-8ENF2673V
21	R6	1	17.4k	RES SMD 17.4K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT17K4
22	R7	1	909k	RES SMD 909K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT909K
23	R12	1	4.22K	RES SMD 4.22K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT4K22
24	R51	1	7.87k	RES SMD 7.87K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT7K87
25	R13A, R13B, R21A, R21B, R50A,B,C,D	8	634k	RES SMD 634K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT634KCT-ND
27	R14	1	0.2	RES SMD 0.2 OHM 1% 5W 4527	Vishay Dale	WSR5R2000FEA
28	RG_H	1	7.5	RES SMD 7.5 OHM 1% 1/4W 1206	Panasonic	ERJ-8RQF7R5V
29	RG_L	1	15	RES SMD 15 OHM 1% 1/4W 1206	Panasonic	ERJ-8ENF15R0V
30	R40, R42	2	1k	RES SMD 1K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT1K00
31	R41	1	100k	RES SMD 100K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT100K
32	R42	1	2.2k	RES SMD 2.2K OHM 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT2K20
33	B1	1	60	FERRITE CHIP 60 OHM 6000MA 1806	Murata	BLM41PG600SN1L
34	T1, T3	2		TERM BLOCK 2POS SIDE ENTRY 10MM	TE Connectivity	282858-2
35	T2	1		CONN TERMINAL BLOCK 2POS 5.08MM	Molex	395443002
36	DH, DL, D5	3	40V	DIODE SCHOTTKY 40V 1A SOD123	Diodes Incorporated	1N5819HW-7-F
37	D7	1	1kV	DIODE GEN PURP 1KV 60A TO247AC	Vishay	VS-60APF10-M3
38	D10	1	2.7	DIODE ZENER 2.7V 500MW SOD123	Diodes Incorporated	MMSZ5223B-7-F
39	U1	1		IC PFC CTRLR AVERAGE CURR 16SOIC	Texas Instruments	UCC3818D
40	U2	1		IC DRIVER MOSF 12A LO SIDE 8SOIC	Micrel	MIC4452YM TR
41	U3	1		IC COMP OTT R-R 44V TSOT-23-5	Linear Technology	LT1716CS5#TRMPBF
42	F1	1		FUSE BLOK CARTRIDGE 500V 10A PCB	Schurter, Inc	0031.8211
43	BR1	1		RECT BRIDGE GPP 15A 800V GBJ	Micro Commercial Co	GBJ1508-BP
44	AC1, AC2, CAI, CAOUT, CT, DRV, EN, GND1,GND2,GND3,GND4, HV, HV_Return, IAC, MOUt, PKLMT, SS, VAOUT, VCC, VFF, Vsense	21		TERMINAL TURRET DBL .082"L	Keystone	1573-2
45	L2	1		CHOKE COMM MODE W/HDR 1mH 10A	Bourns	8108-RC
46	Q2	1		MOSFET N-CH 30V 1.8A MCPH3	On Semiconductor	MCH3475-TL-E
47	HS1	1		FUSE BLOK CARTRIDGE 500V 10A PCB	Schurter, Inc	0031.8201
48	F1 - FUSE Cover	1		Fuse Cover	Schurter, Inc	853.0551
49	L1	1		MPP Core (68Turns, 14 AWG)	Magnetics Inc	55438
50	Q1	1		1.2kV, 45 mOhm Cascode	United silicon Carbide	UJC1210K
51	D1	1	5A	1.2kV, 5A SiC diode	United silicon Carbide	UJ2D1205T

Note: Part numbers in red are for those wishing to use PCB for a 90/260 VAC to to 400 VDC, 1 kW PFC.

9.0 Schematic