Full Bridge LLC ZVS Resonant Converter Based on Gen2 SiC Power MOSFET

Cree Power Application Engineering

Rev. 2

CREE

www.cree.com

Overview

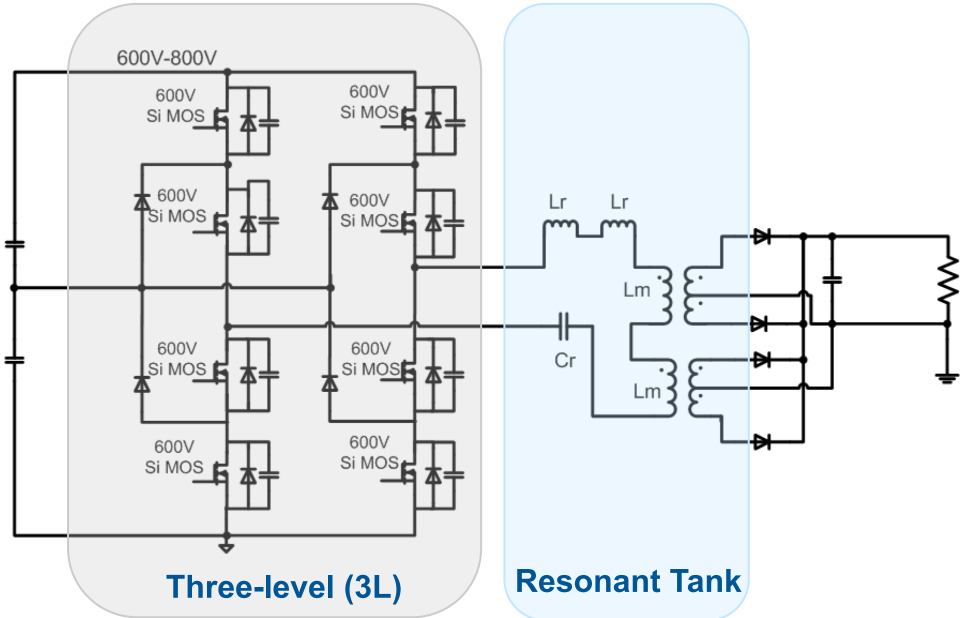
ZVS converters are typically used in the following applications:

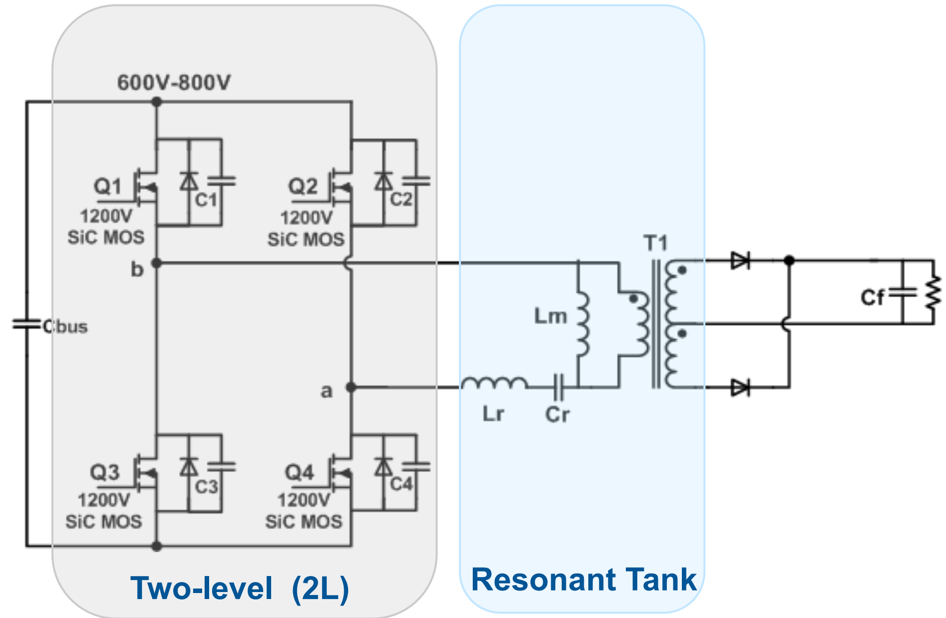
- Industrial power supply
- Telecommunications power supply
- EV Battery charger

SiC MOSFETs can simplify ZVS converter designs AND offer the following advantages:

- Lower system cost
- Improved performance
- Smaller size

Simplify with SiC – Example 1





Silicon:
600V MOS
Three-level LLC Full bridge

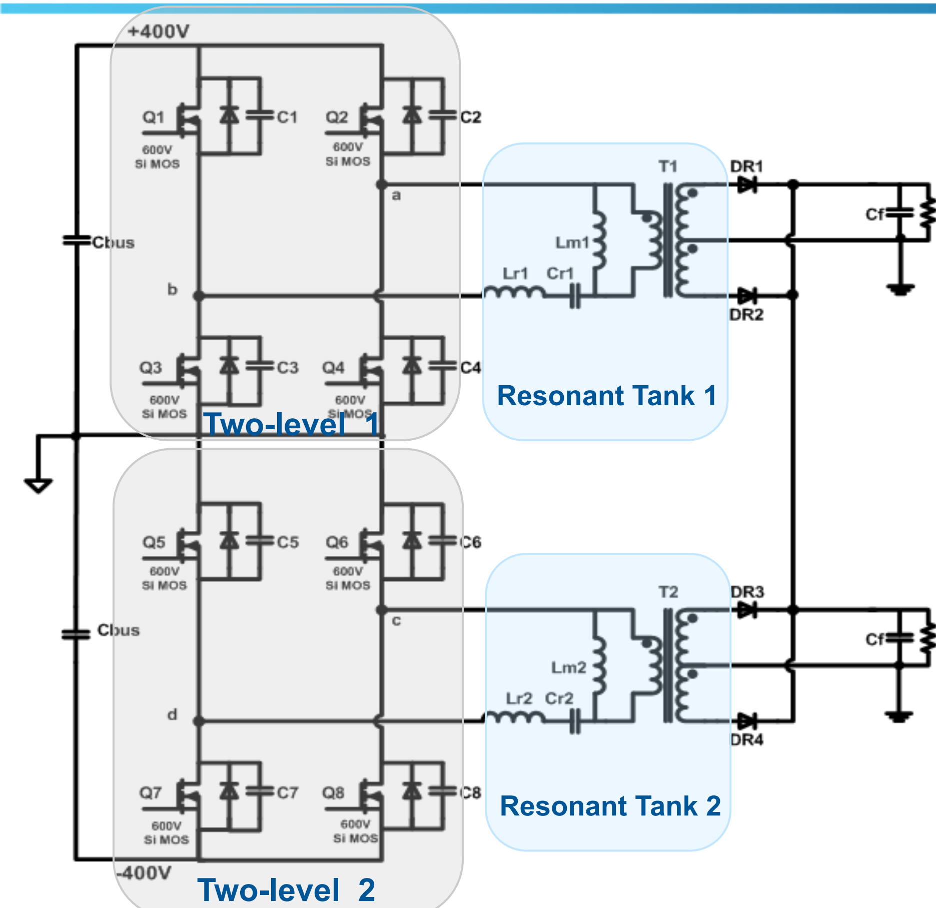
Typical switching frequency:
100KHZ-200KHZ

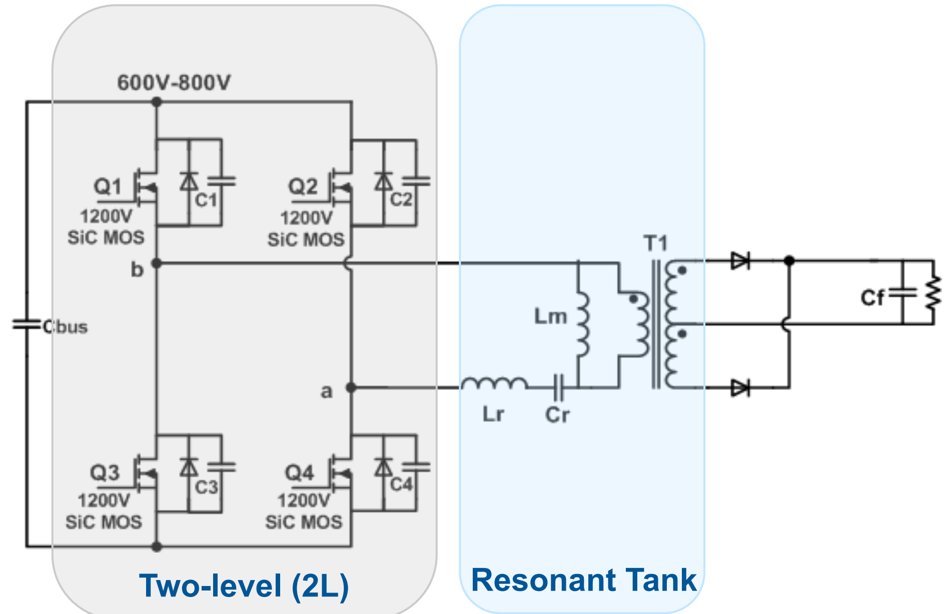
Si to SiC

Silicon Carbide:
1200V SiC MOS
Two-level FB ZVS LLC resonant

Target switching:
>200KZ-400KHZ
Can reduce BOM cost and improve efficiency

Simplify with SiC – Example 2





Silicon:
600V MOS
Interleaved Two level LLC Full bridge

Typical switching frequency:
100KHZ-200KHZ

Si to SiC

Silicon Carbide:
1200V SiC MOS
Two-level FB ZVS LLC resonant

Target switching:
>200KZ-400KHZ
Can reduce BOM cost and improve efficiency

TO-247 MOSFET Parameters Comparison (Gen2 1.2kV SiC MOSFET Vs 650V Si CoolMOS)

Parameters	SiC MOS C2M0160120D	Si CoolMOS SPW47N60CFD	Si CoolMOS IPW65R110CFD
Breakdown Voltage @Tjmax	1200V	650V	650V
Rdson @Tc=110degC	0.22Ω	0.14Ω (x2 for three-level)	0.19Ω (x2 for three-level)
Ciss @f=1MHZ VDS=100V	527pF	7700pF	3240pF
Coss @f=1MHz VDS=100V	100pF	300pF	160pF
Crss @f=1MHz VDS=100V	5pF	10pF	8pF
Td(on)V Turn on delay time	7ns (VDD=800V)	30ns (VDD=400V)	16ns(VDD=400V)
Td(off)V Turn off delay time	13ns (VDD=800V)	100ns(VDD=400V)	68ns(VDD=400V)
Tr Rise time	12ns (VDD=800V)	30ns(VDD=400V)	11ns(VDD=400V)
Tf Fall time	7ns (VDD=800V)	15ns(VDD=400V)	6ns(VDD=400V)
Qg, typ	32.6nC	248nC	118nC
Body diode reverse recovery time trr	35ns	210ns	150ns
Body diode charge Qrr	0.120uC	2uC	0.8uC

Note: The comparison is based on the datasheets

Gen2 SiC MOSFET Advantage in ZVS Converters

- Over 1.2kV blocking voltage.

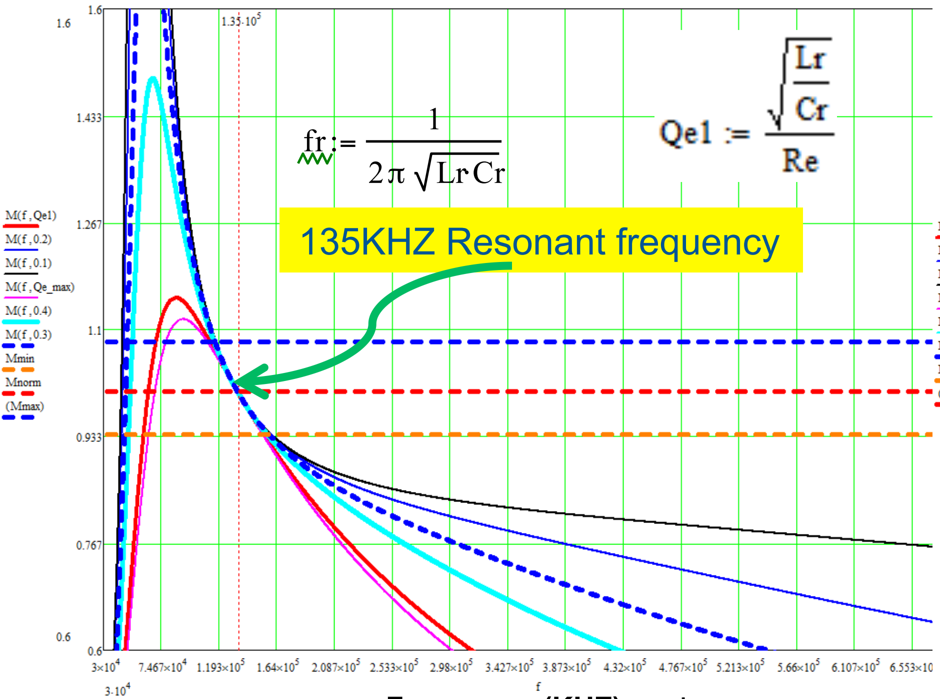
Simplifies Topology

- Low R_{dson} to reduce conduction losses.
- Lower turn off losses due to short fall time and low C_{oss}.
- Short turn off delay time can reduce dead time.
- Lower Q_g will allow lower gate drive losses when switching frequency is high.
- Low body diode t_{rr} and Q_{rr}, which will reduce diode switching losses and electrical noise due to short reverse recovery time.

Increases efficiency and power density.

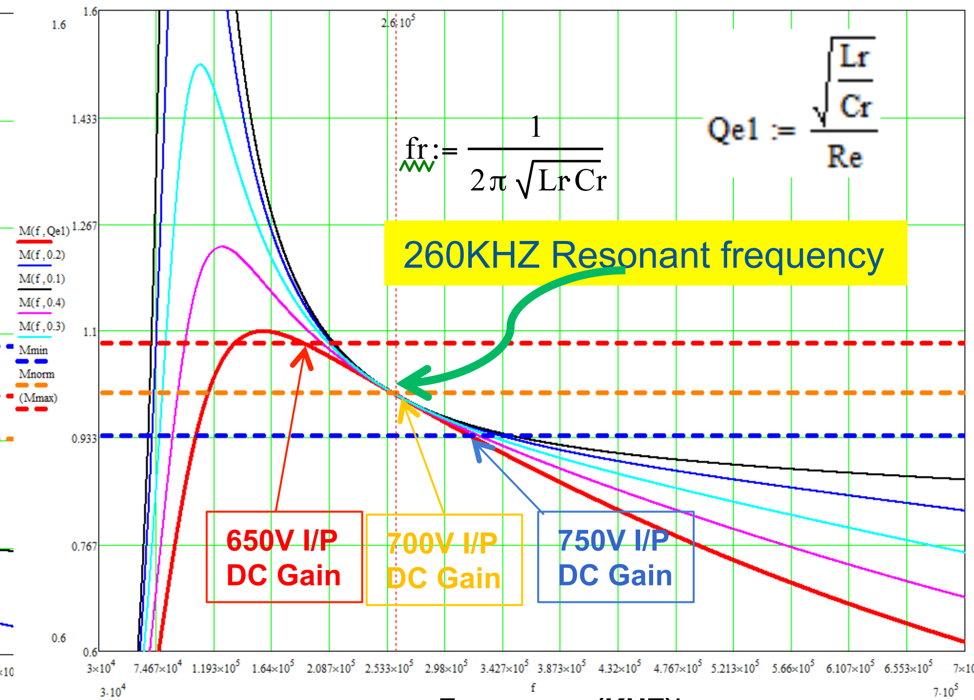
DC Gain Design with Resonant Tank Parameters

Voltage Gain (M)



Frequency (KHZ)

Voltage Gain (M)



Frequency (KHZ)

Large passive LLC resonant tank

Lm=150uH
Lr=35uH
Cr=40nF

Si to SiC

DC Gain Curve

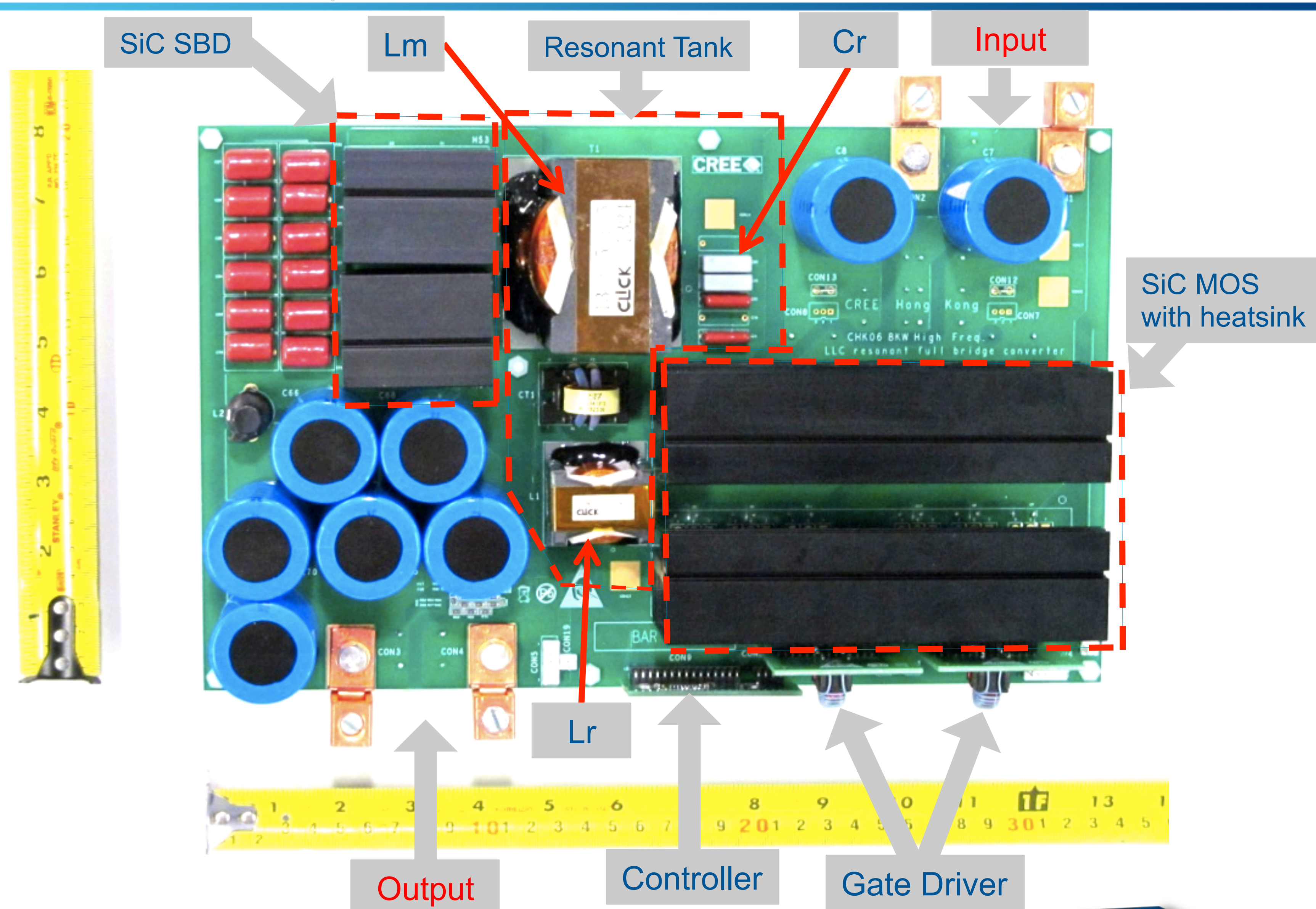
Small passive LLC resonant tank

Lm=100uH
Lr=15uH
Cr=25nF

8KW Full Bridge LLC ZVS Resonant Converter Specification

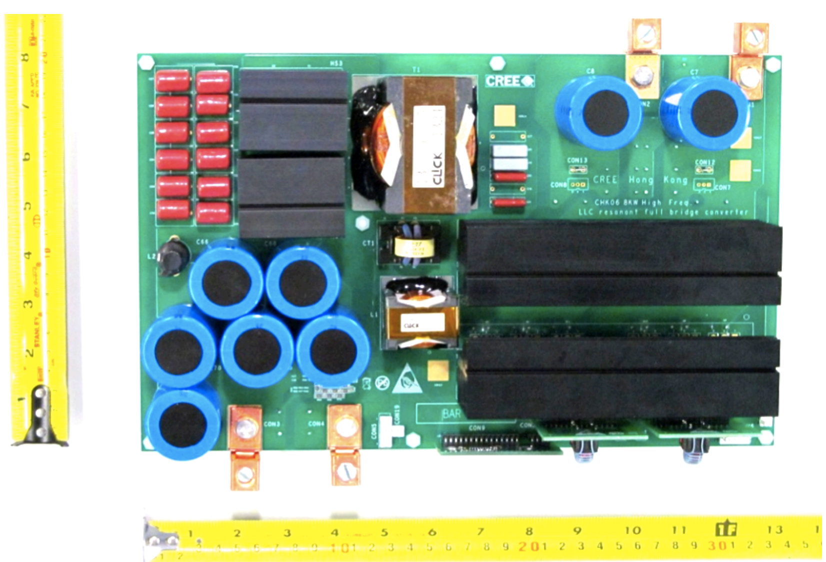
Item	Parameters
Input Voltage	650Vdc-750Vdc
Rated Input Voltage	700Vdc
Output Voltage	270Vdc
Full loading Current	28A
Input Power	8KW
Resonant Frequency	265KHZ
Frequency Range	230KHZ-320KHZ
Efficiency	>98%
Board Size	8"x12.5"x3.5"
Power Density	>35W/inch^3

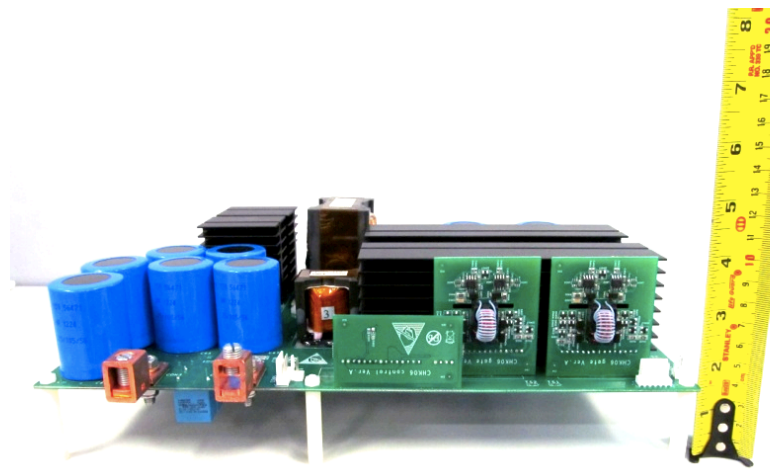
Board Size of 8KW Full Bridge LLC Resonant Converter (Size: 8”x12.5”x3.5”)



Three-Level with Si Vs Two-level with SiC (8-10KW case)

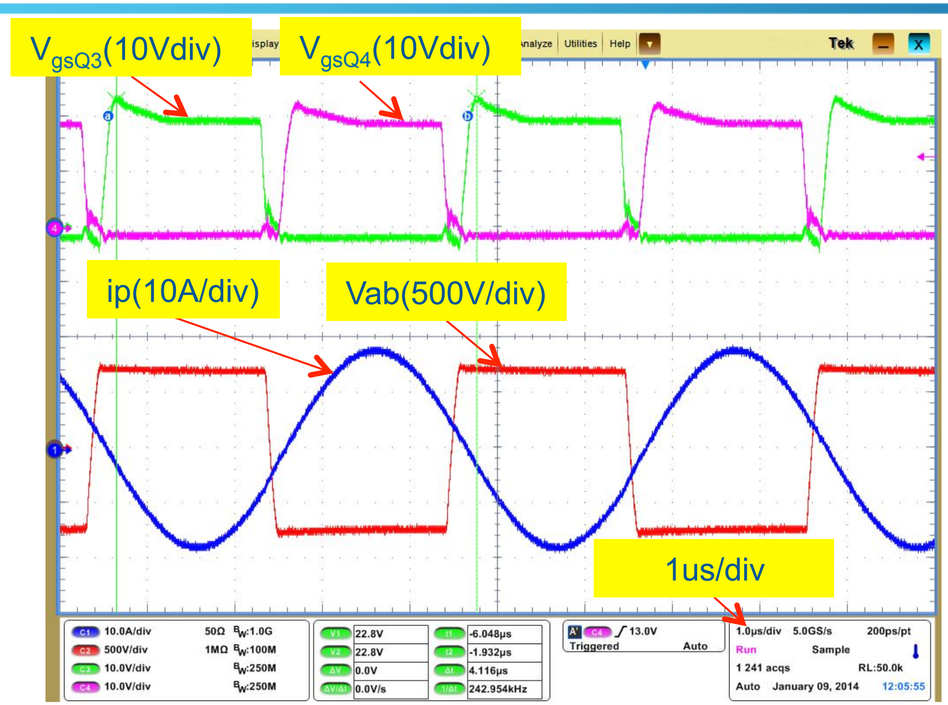
Items	Three-level FB w/ Si MOS @ 120KHZ resonant freq.	Two-level FB w/ SiC MOS @ 260KHZ resonant freq.
MOSFETs	16pcs SPW47N60CFD	8pcs C2M0160120D
Flying diode	4pcs	None
Resonant Inductor	2pcs PQ3535	1pcs PQ3535 Lr=15uH
Magnetize transformer	2pcs PQ5050	1pcs PQ6560 Lm=100uH
Resonant Capacitors	35nF	25nF
MOS Drivers	8pcs	4pcs

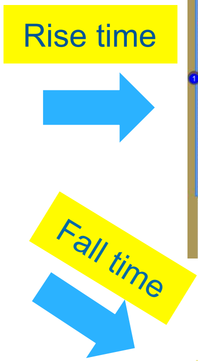


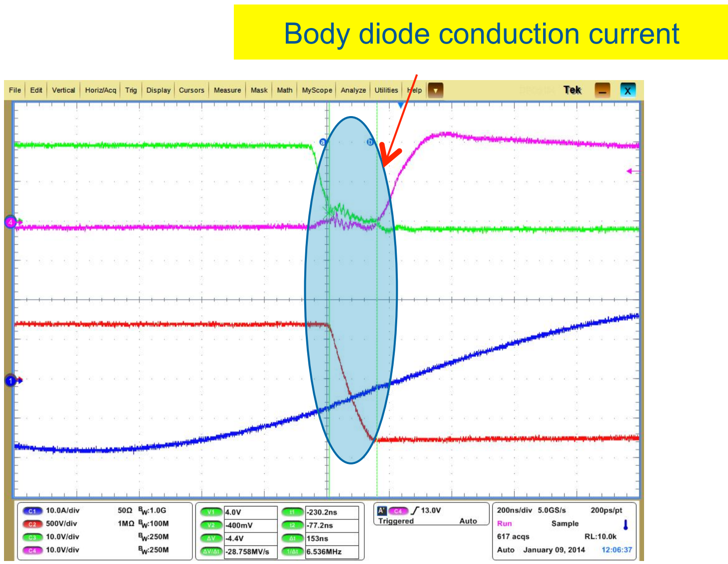


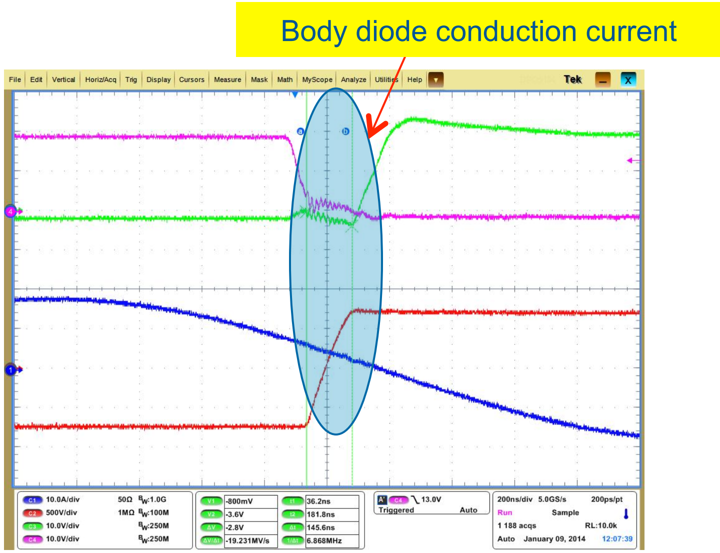
Waveforms

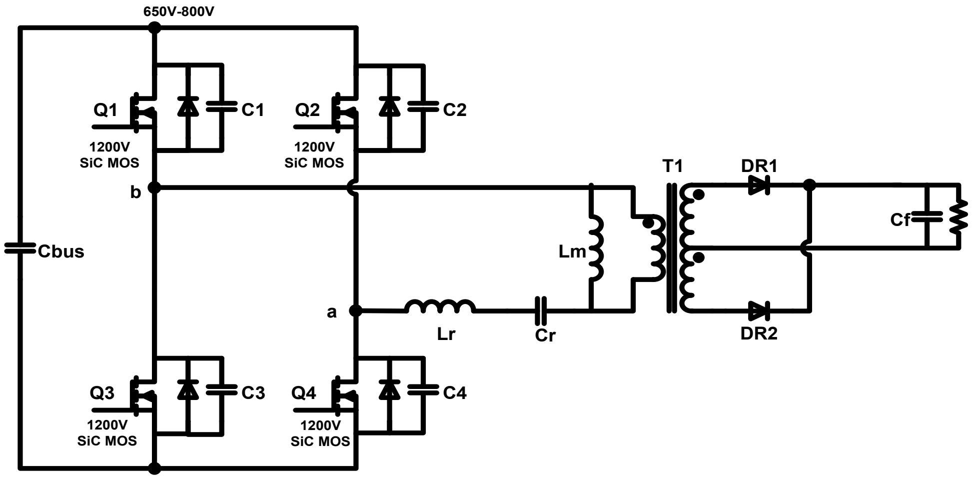
Full Loading with 28A/270V and 700Vdc input



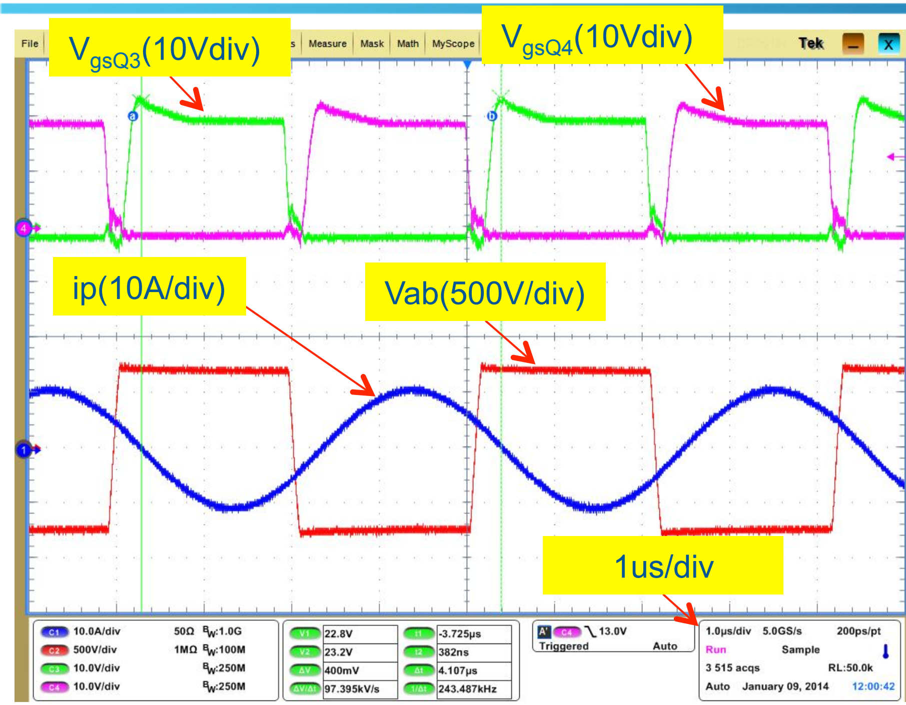




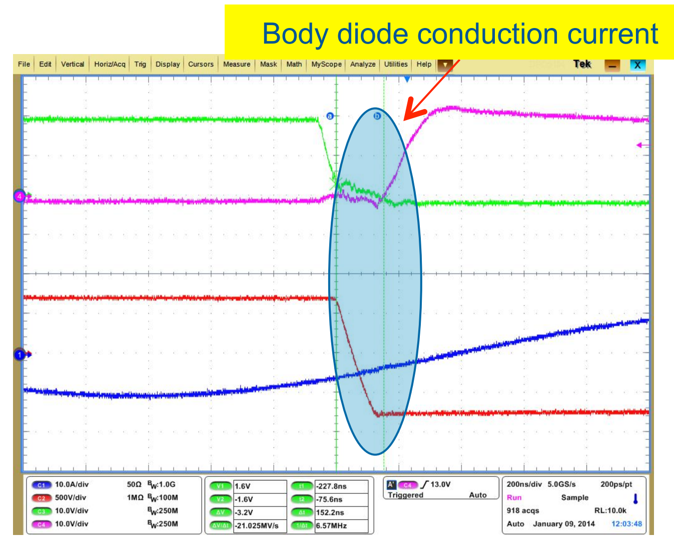




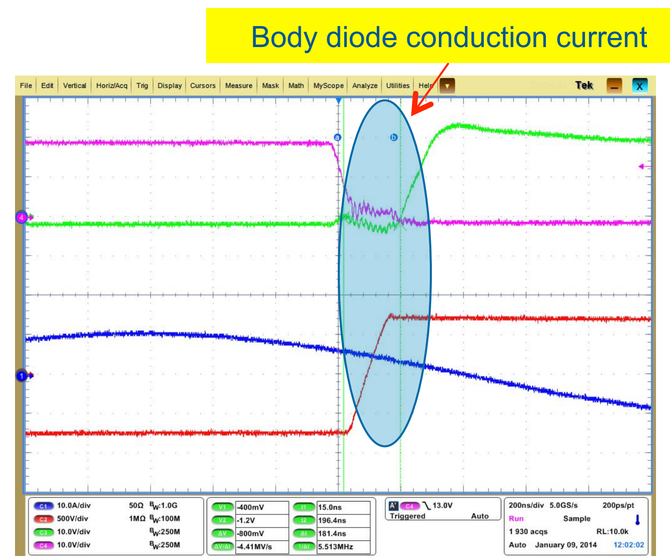
Half Loading with 14A/270V and 700Vdc input

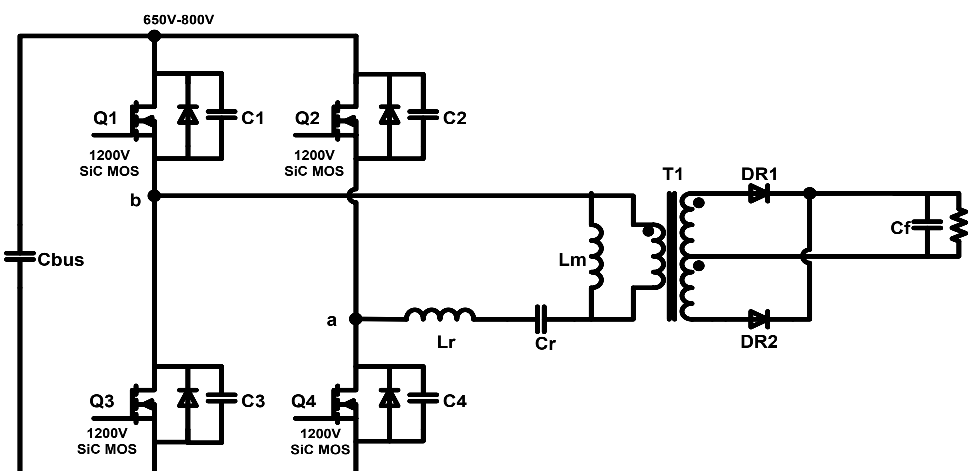


Rise time

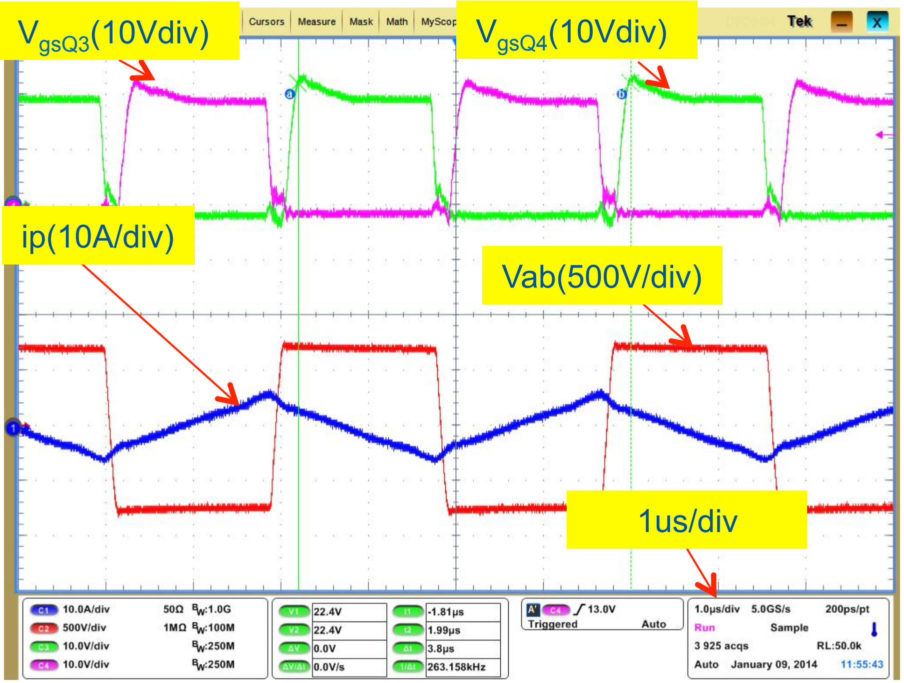


Fall time

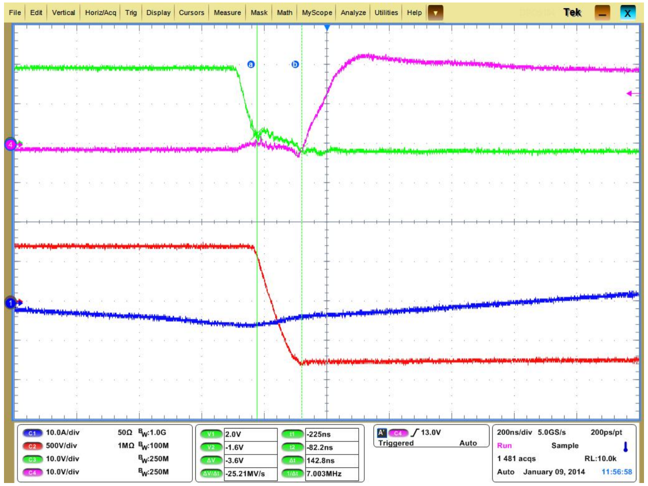




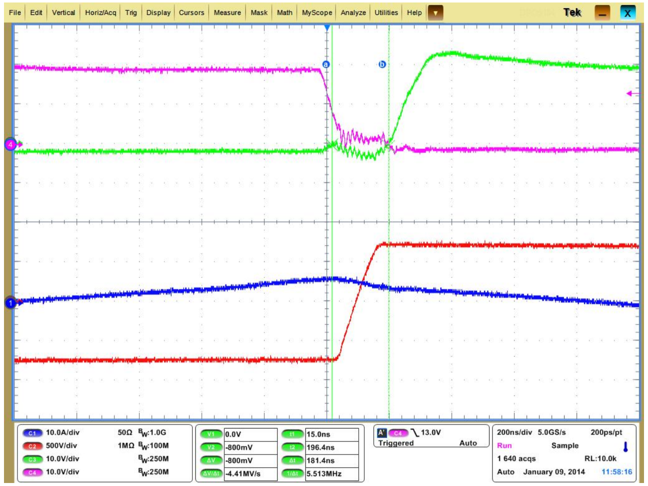
Min Loading with 2A/270V and 700Vdc input

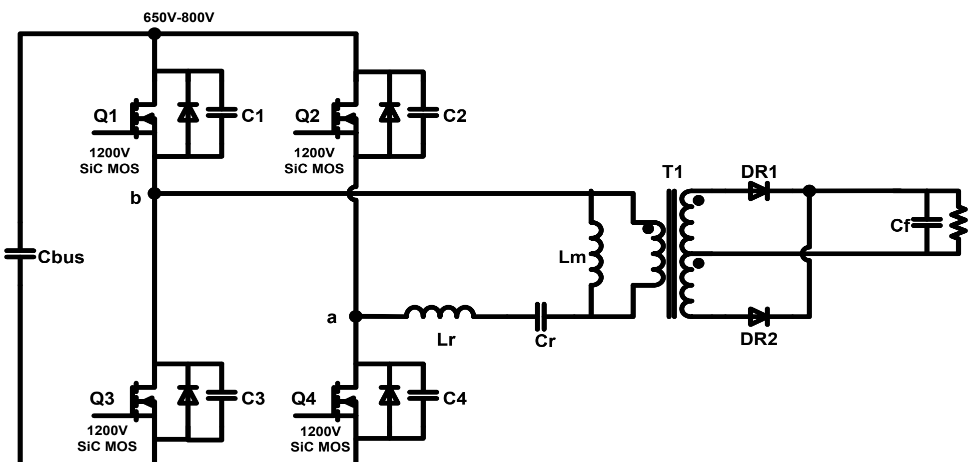


Rise time

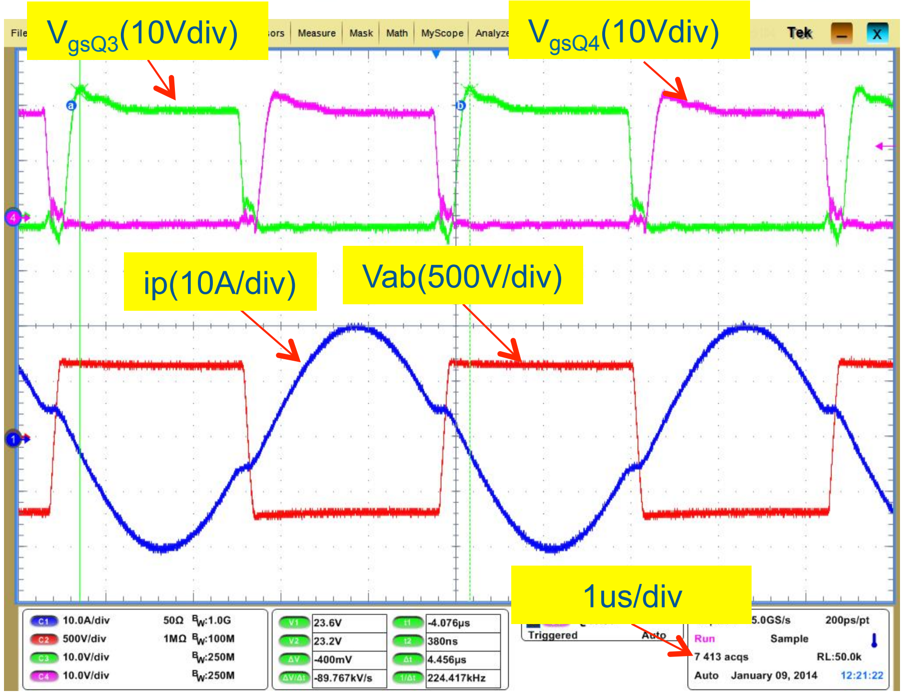


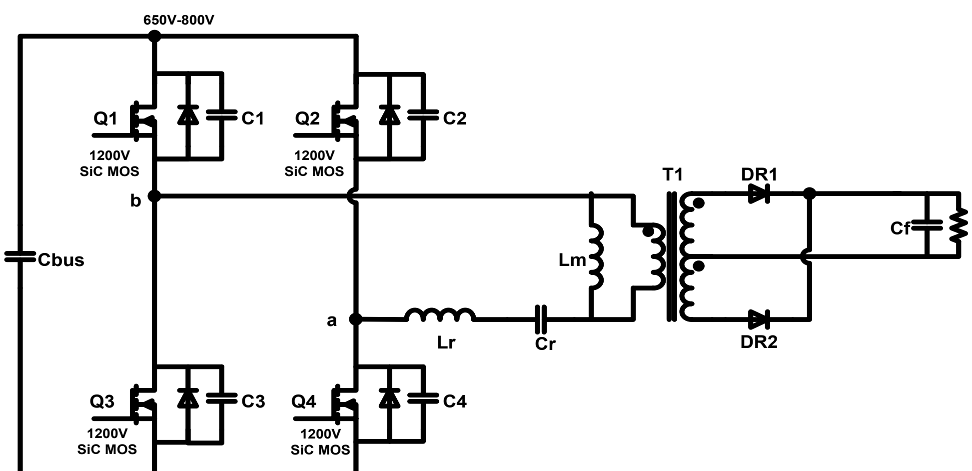
Fall time



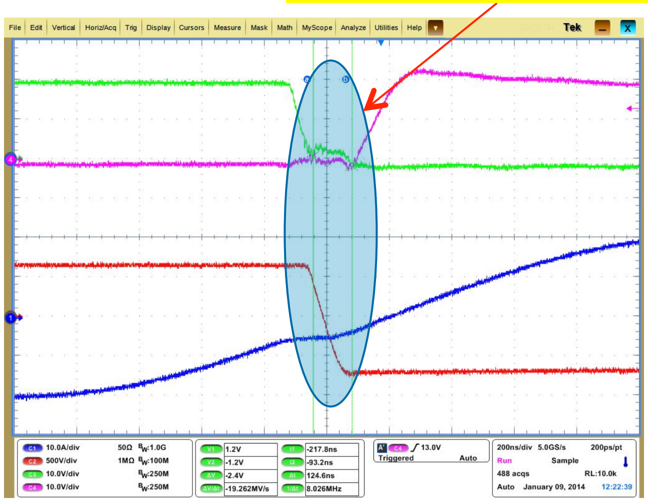


Full Loading with 28A/270V and 650Vdc input

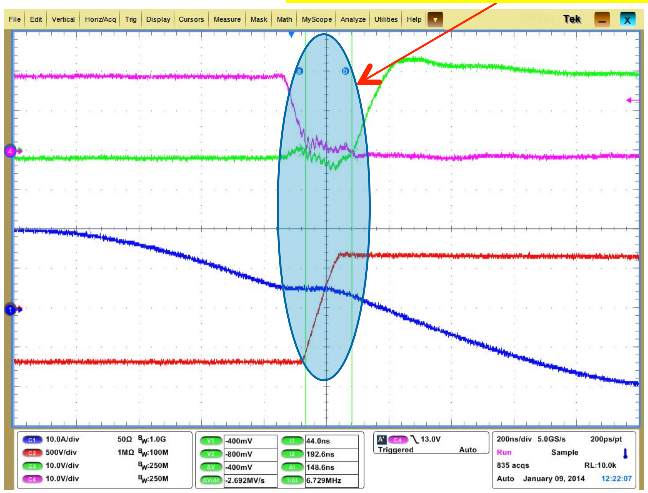




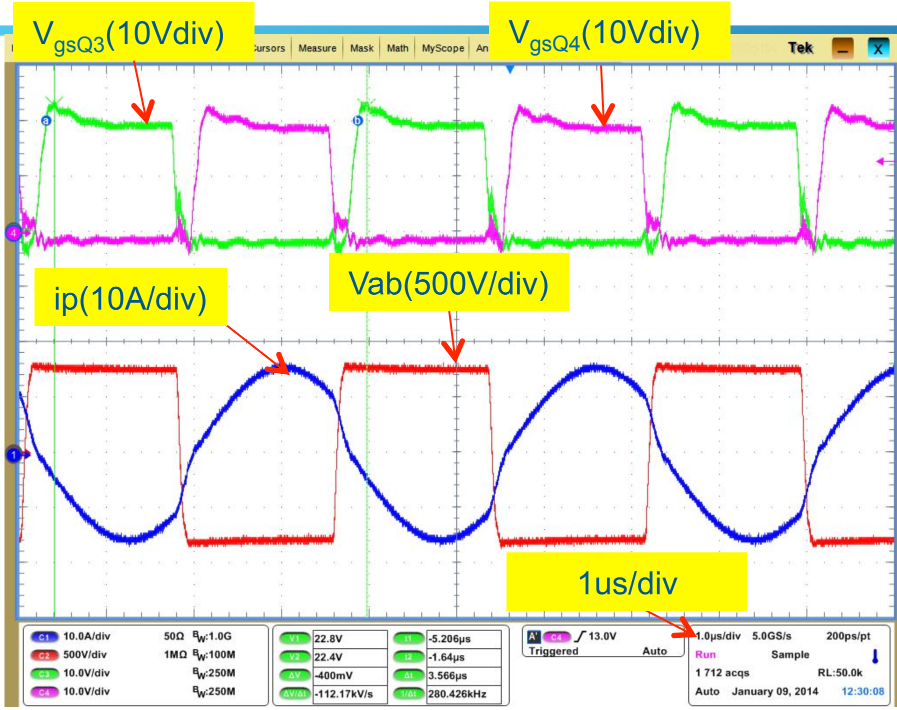
Rise time



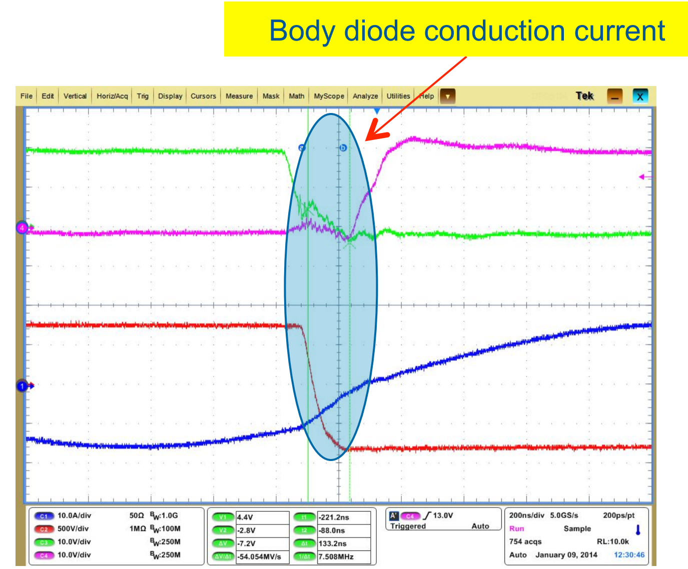
Fall time



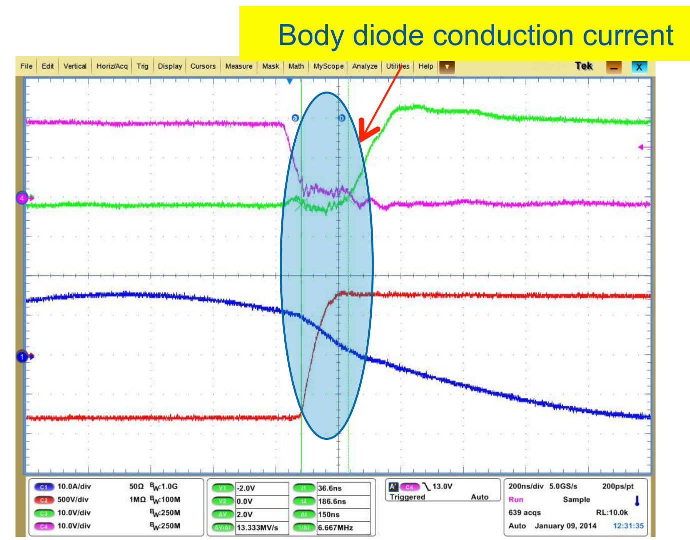
Full Loading with 28A/270V and 750Vdc input

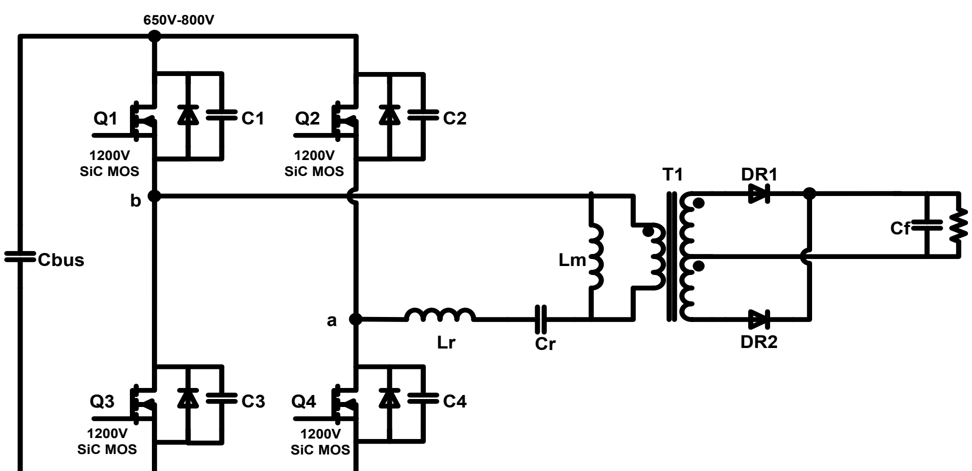


Rise time



Fall time





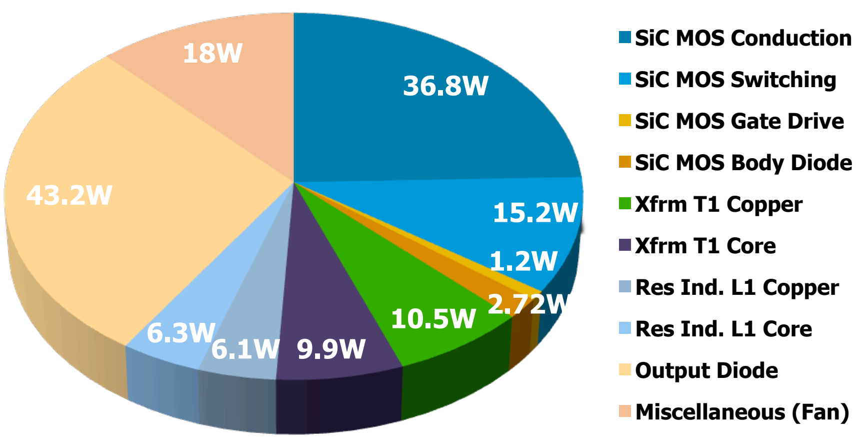
Scenario One: High Efficiency, Dual SiC MOSFET in parallel per Switch

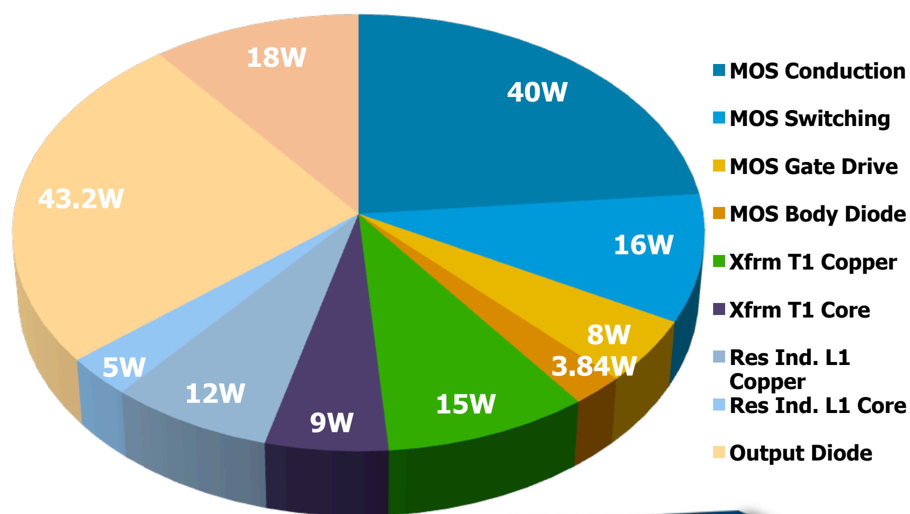
(SiC C2M0160120D Vs Si SPW47N60CFD)

Calculation Losses Breakdown (700Vdc Input and 28A Output full load) @265KHZ SiC 2L and 135KHZ Si 3L (Dual MOS per switch)

SiC Two Level @260KHZ	Each Loss (W)	Qty	Total Loss (W)	Each Item Total Loss (W)
SiC MOS Conduction	4.6	8	36.8	
SiC MOS Switching	1.9	8	15.2	
SiC MOS Gate Drive	0.15	8	1.2	
SiC MOS Body Diode	0.34	8	2.72	55.92
Xfrm T1 PQ60 Copper	10.5	1	10.5	
Xfrm T1 PQ60 Core	9.9	1	9.9	20.4
Res Ind. L1 PQ35 Copper	6.1	1	6.1	
Res Ind. L1 PQ35 Core	6.3	1	6.3	12.4
Output Diode	10.8	4	43.2	43.2
Miscellaneous (w/Fan)	18	1	18	18
Target Eff.	98.1%		Total Loss	149.92W

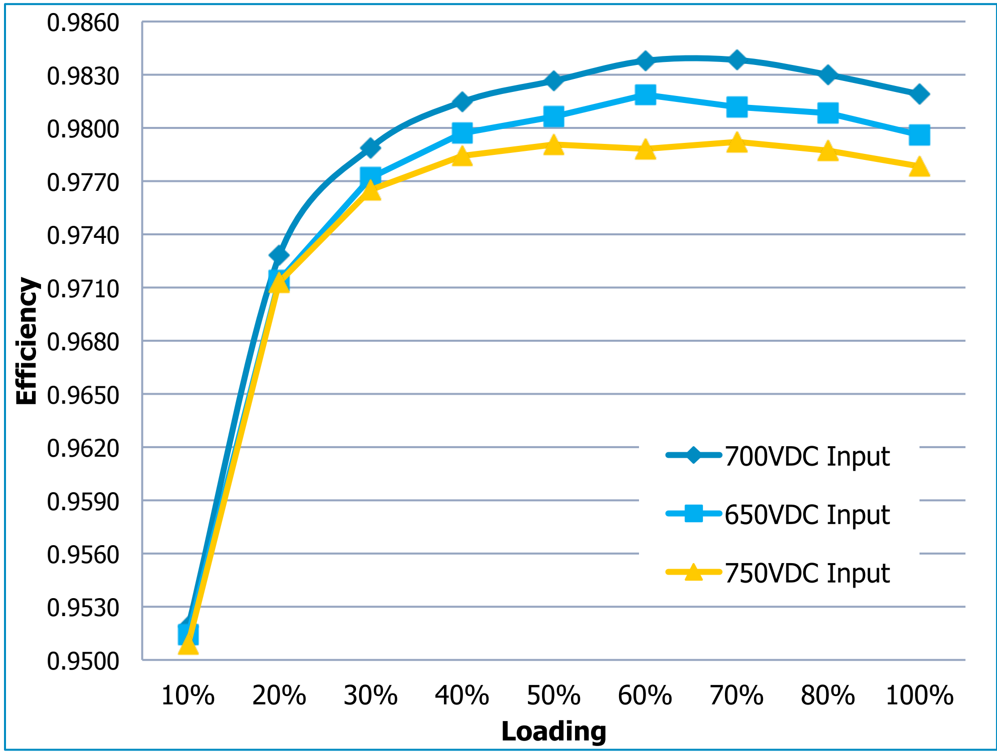
Si Three-Level @135KHZ	Each Loss (W)	Qty	Total Loss (W)	Total Loss (W)
Si MOS Conduction	2.5	16	40	
Si MOS Switching	1	16	16	
Si MOS Gate Drive	0.5	16	8	
Si MOS Body Diode	0.24	16	3.84	67.84
Xfrm T1 PQ50 Copper	7.5	2	15	
Xfrm T1 PQ50 Core	4.5	2	9	24
Res Ind. L1 PQ35 Copper	6	2	12	
Res Ind. L1 PQ35 Core	2.5	2	5	17
Output Diode	10.8	4	43.2	43.2
Miscellaneous (w/Fan)	18	1	18	18
Efficiency	97.8%		Total	170.04W





Efficiency with loading with different Input Voltage (Dual MOSFET per Switch)

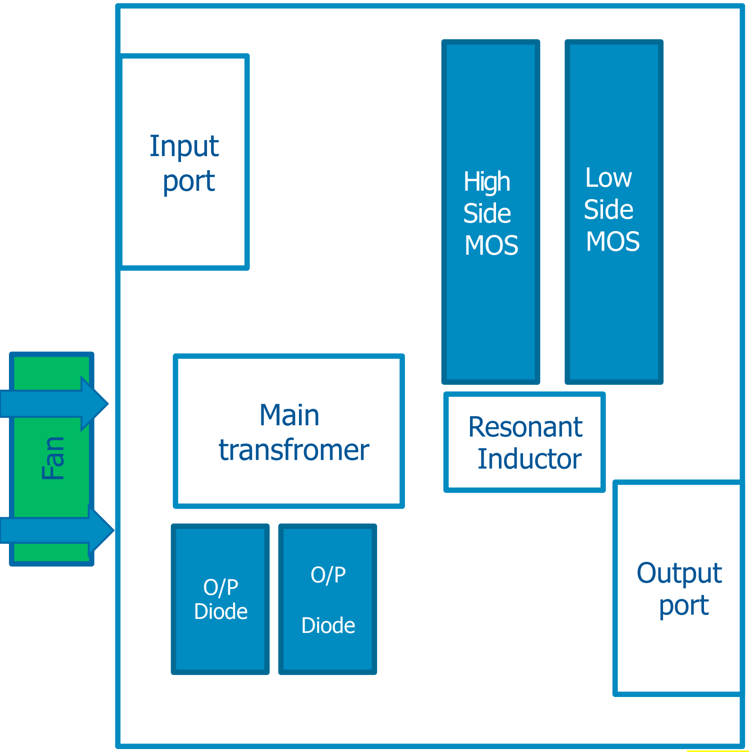
Vin (V)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	Eff
699.44	0.8951	626.07	274.76	2.1227	583.23	0.9316
699.41	1.2687	887.34	273.13	3.0924	844.63	0.9519
699.43	2.4157	1689.61	272.99	6.0210	1643.67	0.9728
699.46	3.5119	2456.43	273.58	8.7893	2404.58	0.9789
699.44	4.6993	3286.88	274.07	11.7706	3225.97	0.9815
699.45	5.9640	4171.52	274.26	14.9463	4099.17	0.9827
699.45	6.9910	4889.85	274.31	17.5370	4810.57	0.9838
699.45	8.324	5822.22	274.15	20.8940	5728.09	0.9838
699.45	9.3	6504.89	273.95	23.3410	6394.27	0.9830
699.46	10.973	7675.17	273.42	27.5630	7536.28	0.9819

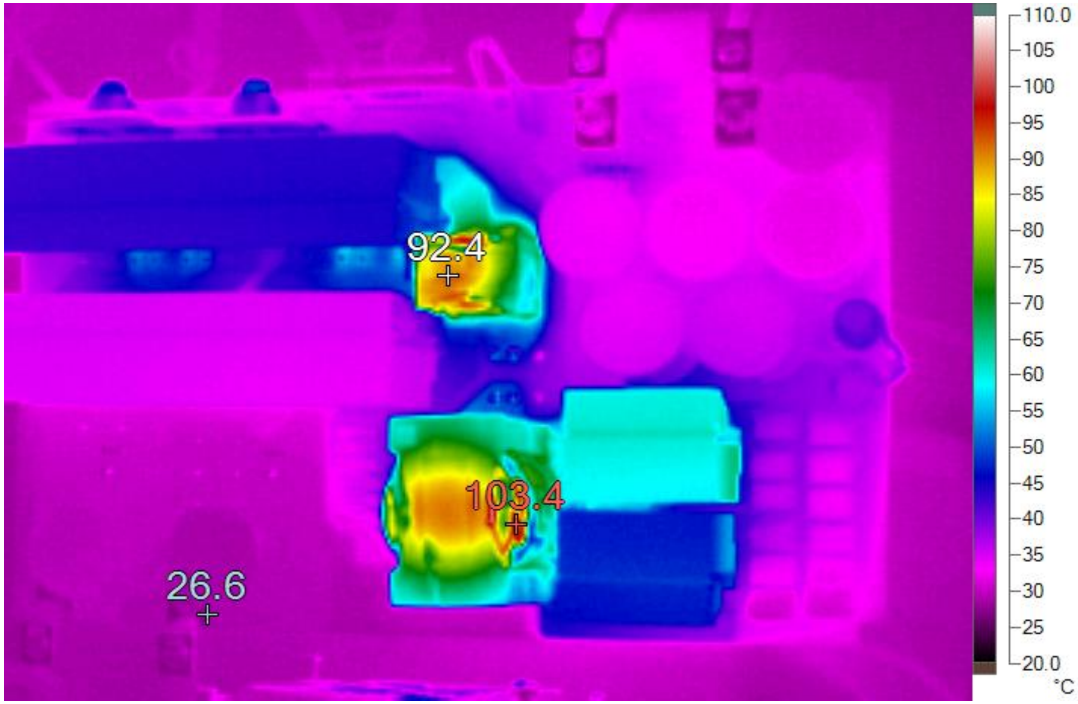


Note:

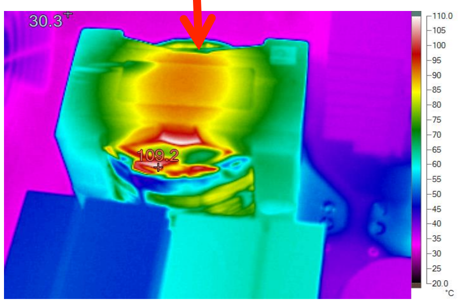
- **Fan cooling the system and efficiency does not include the auxiliary power supply losses for efficiency test**
- **One 12W fan to cooling the system**
- **Yokogawa WT230 power meter is used to measure input and output current**
- **Each data is measured after 3min operation**

Thermal Performance @ full load with fan cooling system (Dual MOSFET per switch)

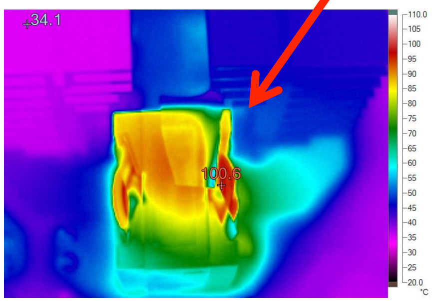




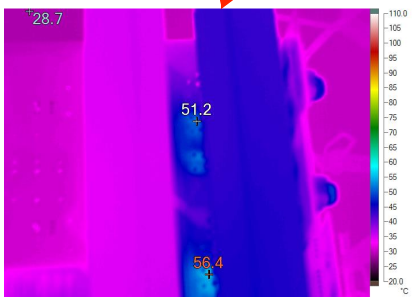
Transformer Tr



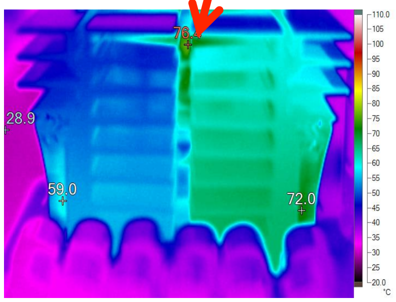
Resonant Inductor Lr



SiC MOS Heatsink



Output SiC Diode



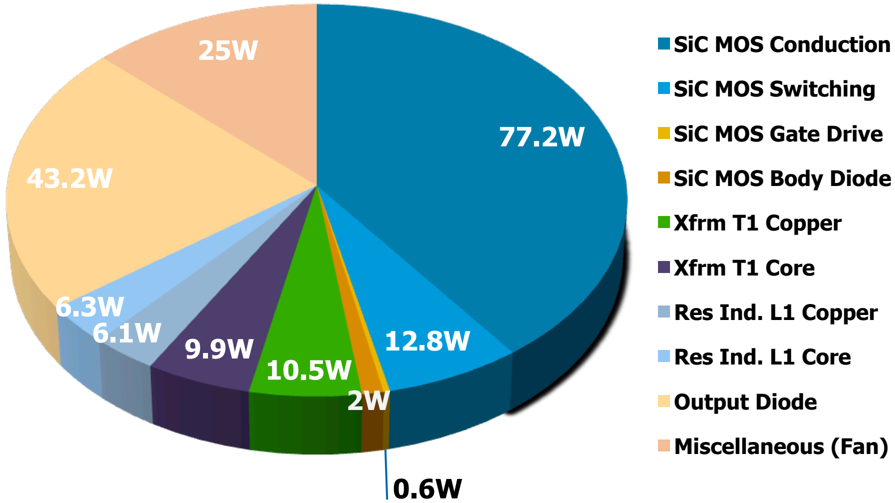
Scenario Two: Low Cost, Single SiC MOSFET per Switch

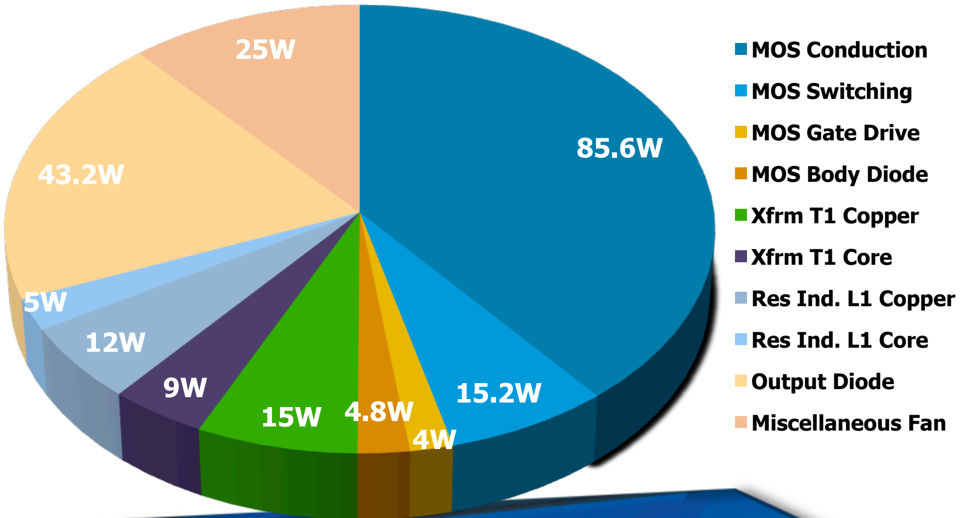
(SiC C2M0160120D Vs Si SPW47N60CFD)

Calculation Losses Breakdown (700Vdc Input and 28A Output full load) @265KHZ SiC 2L and 135KHZ Si 3L (Single MOSFET per switch)

SiC Two Level @260KHZ	Each Loss (W)	Qty	Total Loss (W)	Each Item Total Loss (W)
SiC MOS Conduction	19.3	4	77.2	
SiC MOS Switching	3.2	4	12.8	
SiC MOS Gate Drive	0.15	4	0.6	
SiC MOS Body Diode	0.5	4	2	92.6
Xfrm T1 PQ60 Copper	10.5	1	10.5	
Xfrm T1 PQ60 Core	9.9	1	9.9	20.4
Res Ind. L1 PQ35 Copper	6.1	1	6.1	
Res Ind. L1 PQ35 Core	6.3	1	6.3	12.4
Output Diode	10.8	4	43.2	43.2
Miscellaneous (w/Fan)	25	1	25	25
Target Eff.	97.6%		Total Loss	193.6W

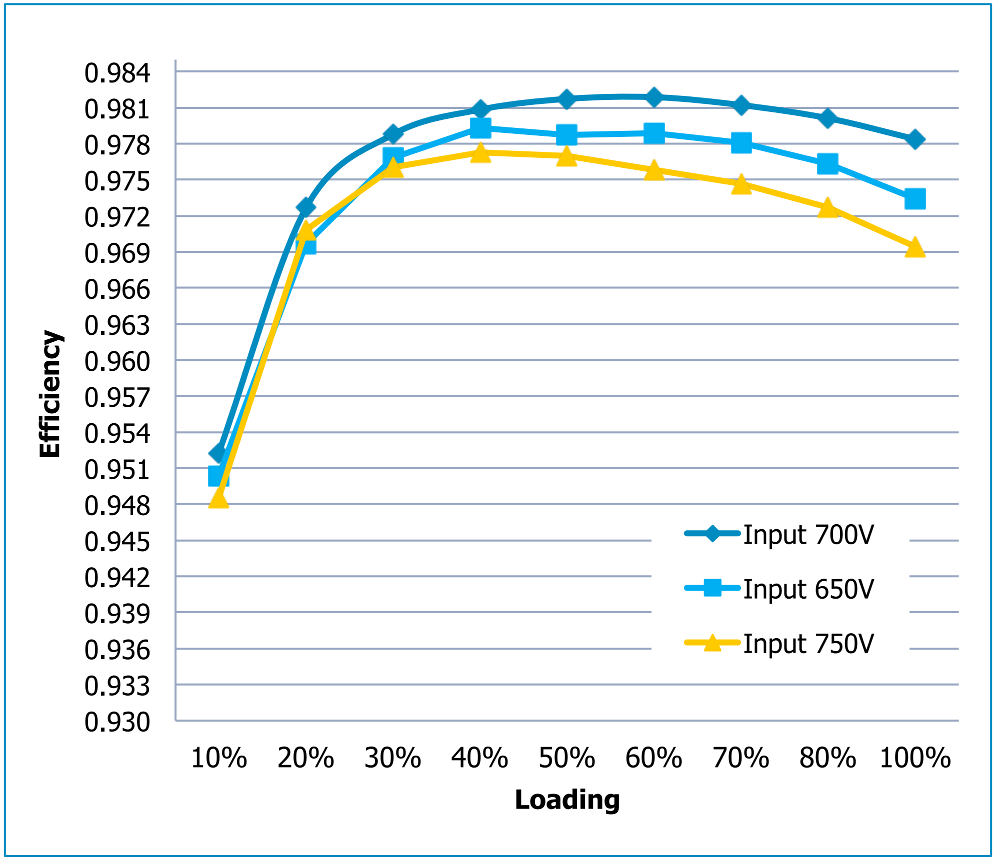
Si Three-Level @135KHZ	Each Loss (W)	Qty	Total Loss (W)	Total Loss (W)
Si MOS Conduction	10.7	8	85.6	
Si MOS Switching	1.9	8	15.2	
Si MOS Gate Drive	0.5	8	4	
Si MOS Body Diode	0.6	8	4.8	109.6
Xfrm T1 PQ50 Copper	7.5	2	15	
Xfrm T1 PQ50 Core	4.5	2	9	24
Res Ind. L1 PQ35 Copper	6	2	12	
Res Ind. L1 PQ35 Core	2.5	2	5	17
Output Diode	10.8	4	43.2	43.2
Miscellaneous (w/Fan)	25	1	25	25
Efficiency	97.3%		Total	218.8W





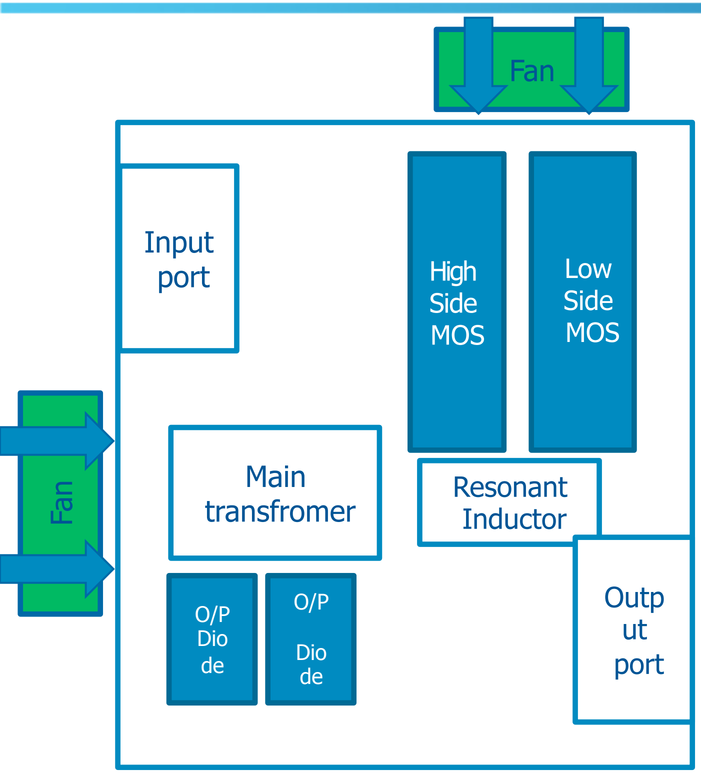
Efficiency with loading with different Input Voltage (Single MOSFET per switch)

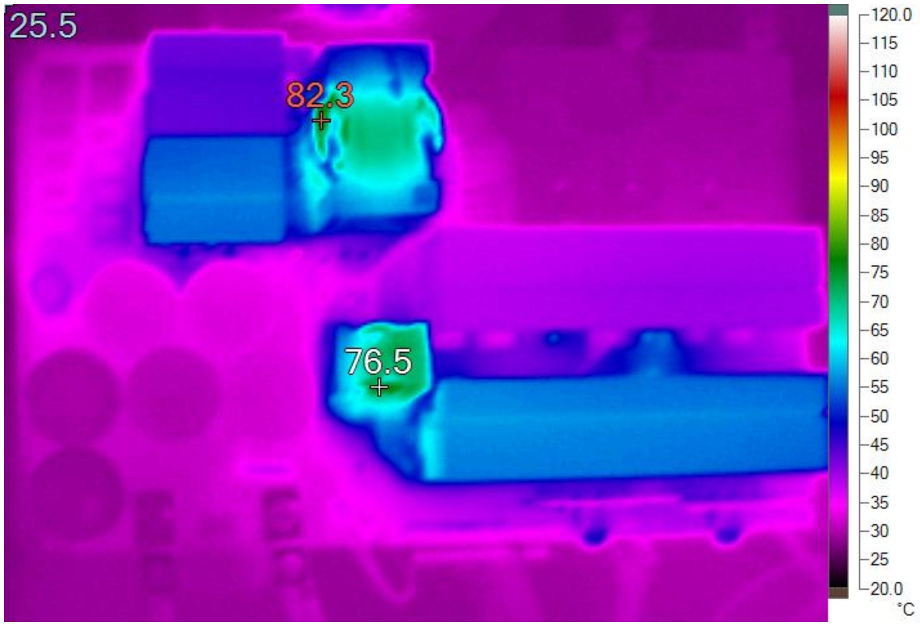
Vin(V)	Iin (A)	Pin(W)	Vout(V)	Iout(A)	Pout(W)	Eff
699.34	0.8886	621.43	274.41	2.1173	581.01	0.9349
699.36	1.2630	883.29	273.43	3.0762	841.13	0.9523
699.36	2.3918	1672.73	271.55	5.9916	1627.02	0.9727
699.37	3.4630	2421.92	271.92	8.7177	2370.52	0.9788
699.48	4.6241	3234.47	272.17	11.6563	3172.50	0.9808
699.39	5.8720	4106.82	272.29	14.8070	4031.80	0.9817
699.41	6.9010	4826.63	272.60	17.3850	4739.15	0.9819
699.43	8.262	5778.69	273.01	20.7690	5670.14	0.9812
699.41	9.272	6484.93	273.2	23.2650	6356.00	0.9801
699.43	10.998	7692.33	272.91	27.5770	7526.04	0.9784



Note:
- **Fan cooling the system and efficiency does not include the auxiliary power supply losses for efficiency test**
- **Two 12W fan to cooling the system**
- **Yokogawa WT230 power meter is used to measure input and output current**
- **Each data is measured after 3min operation**

Thermal Performance @ full load with fan cooling system (Single MOSFET per switch)



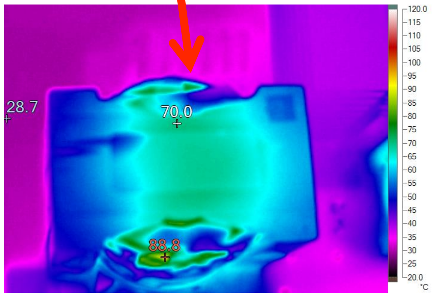


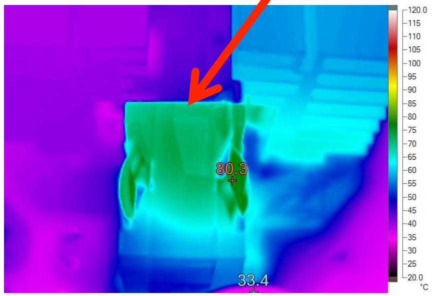
Transformer Tr

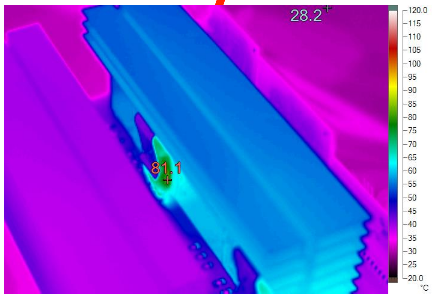
Resonant Inductor Lr

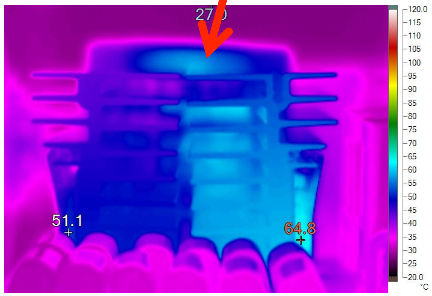
SiC MOS Heatsink

Output SiC Diode

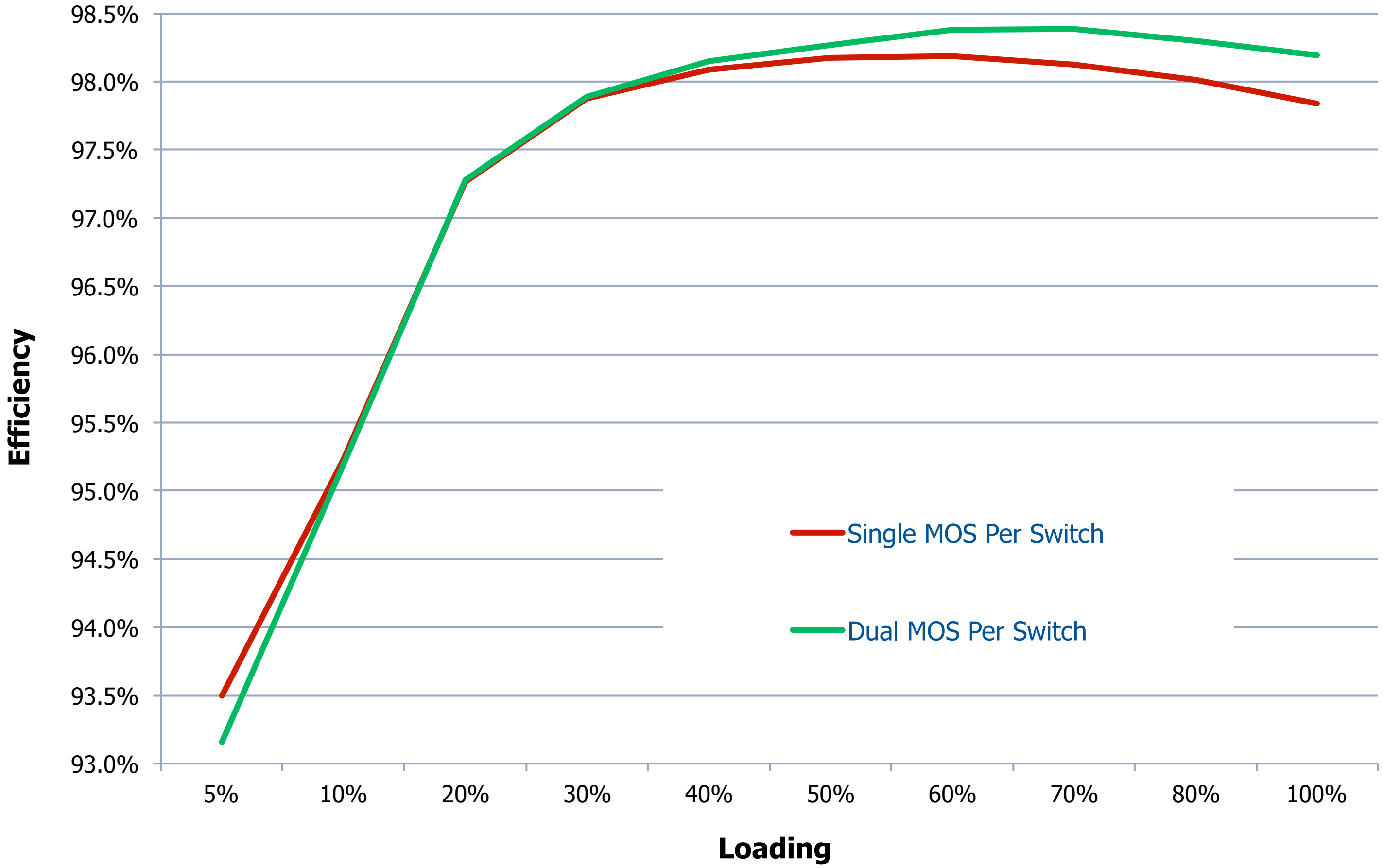






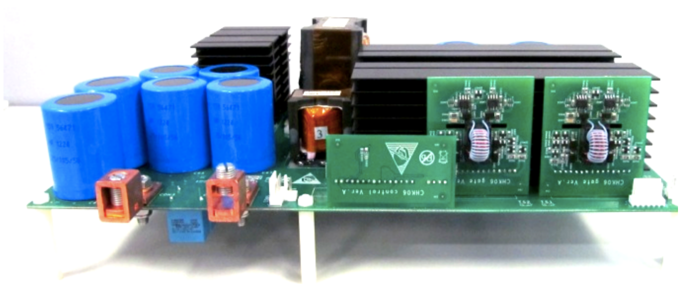


Efficiency Difference
Dual MOSFET vs. Single MOSFET per switch @ 700Vdc Input



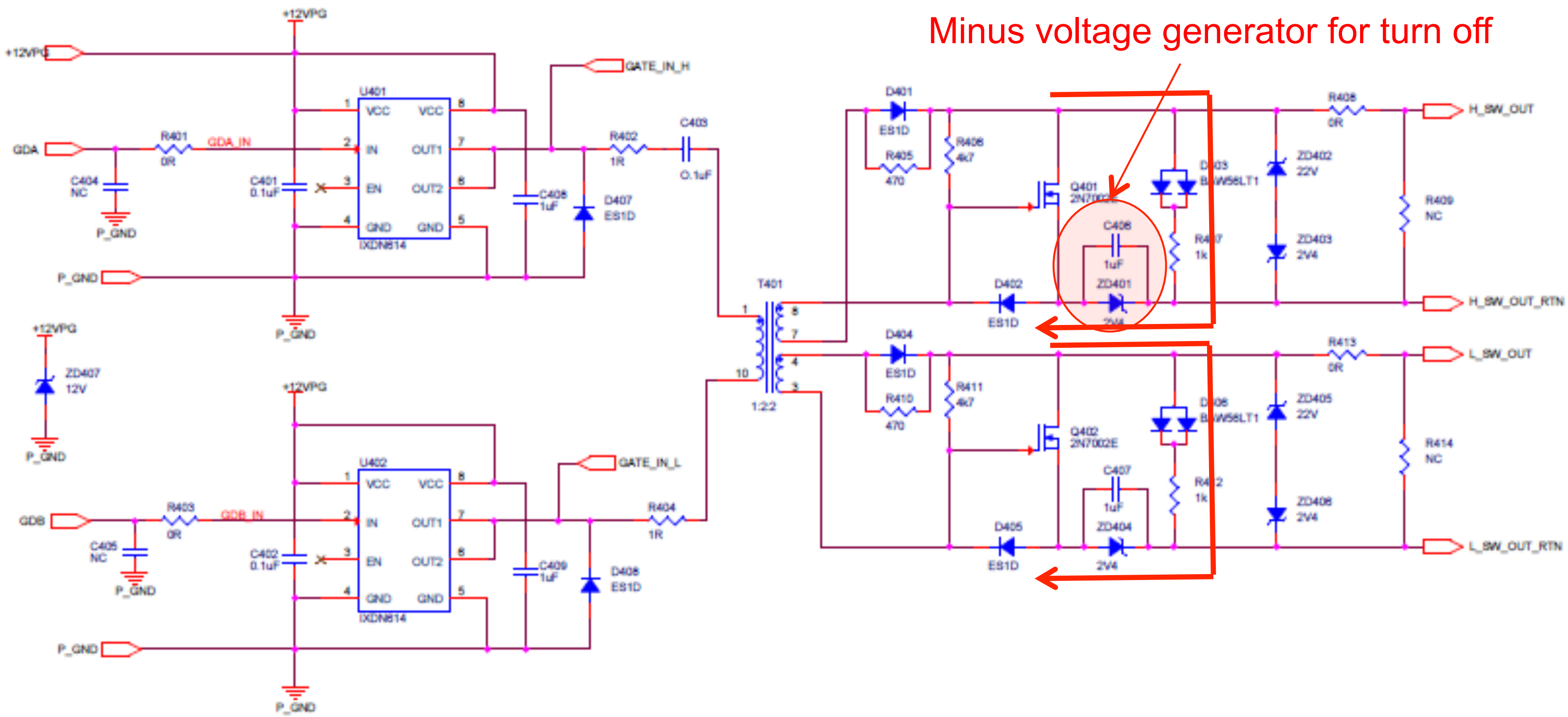
Summary

- Reduce system complexity and lower part count with a simplified 2-Level ZVS topology.
- Optimize solution
  - To Improve efficiency performance.
  - To reduce system cost.
- Reduce system weight and size by designing to a higher resonant frequency.



Appendix:
Simplify SiC MOS driver Circuit for LLC Full Bridge Topology

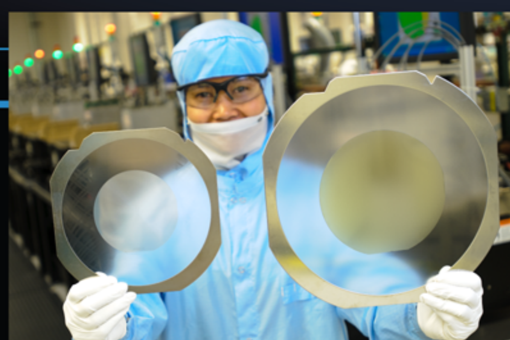
Proposed Full Bridge topology SiC MOS gate drive circuit



- The -ve voltage for turn-off is generated by charging 1uF cap across 2V zener when MOS is turned on.
- The MOSFET on secondary side of gate drive transformer speeds up turn off turn-off of SiC MOS.
- 1:2 gate drive transformer turns ratio allows a single 12V supply voltage for gate drive without any additional voltage supply requirements.

Cree has the global footprint & world-class distribution network to deliver SiC products wherever you need them.

Cree is the leader in Silicon Carbide power semiconductors.



Cree is one of world's fastest-growing power semiconductor manufacturers.

Cree has excellent capitalization.

Cree is vertically integrated—for an efficient supply chain and product traceability.

Cree has the technology roadmap for improved SiC production and cost reduction.