A SiC-Based 60kW LLC Converter with Novel Transformer Design for Improving Voltage Balance

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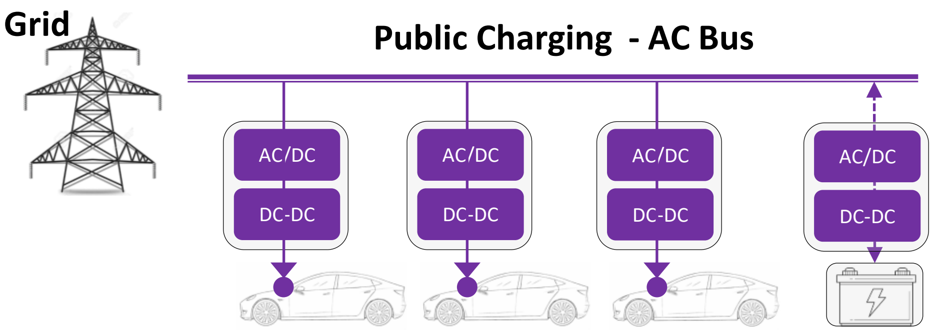
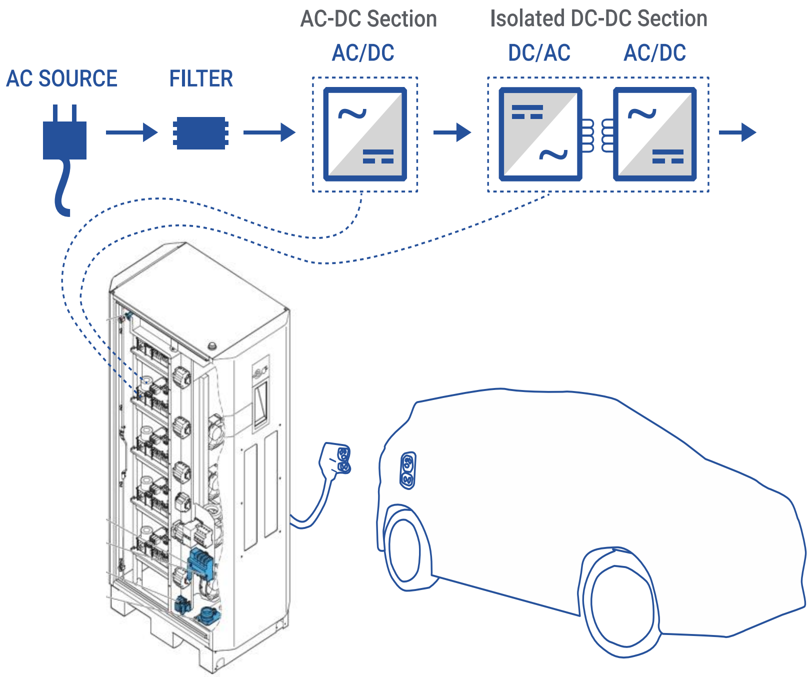
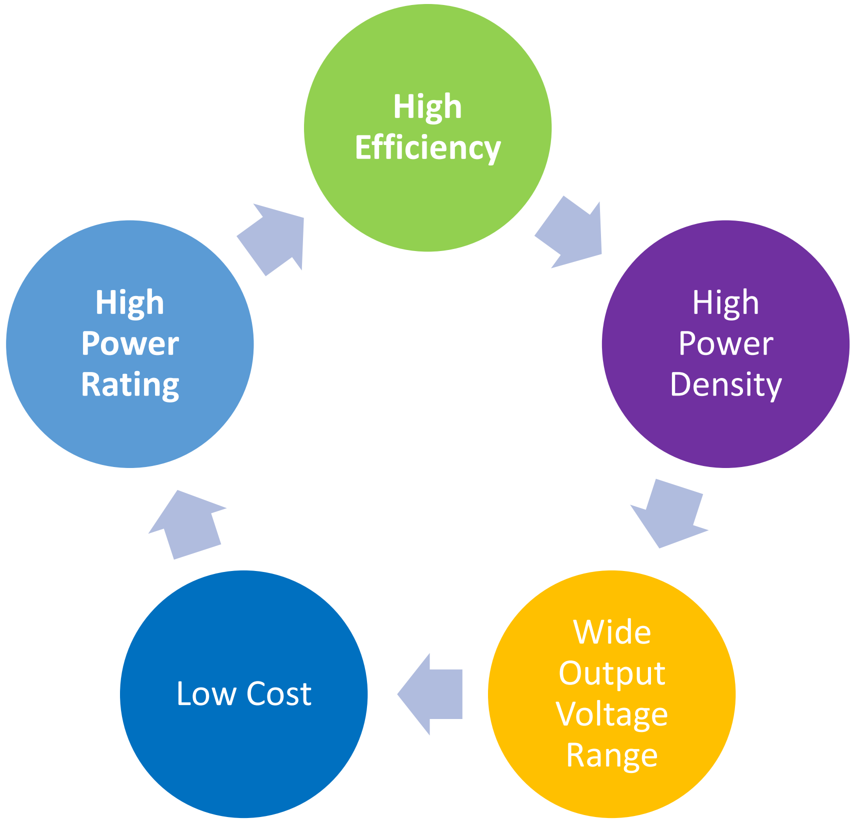
EV DC FAST CHARGING

	DC FAST CHARGERS		
Power	50kW~150kW	150kW~500kW	500kW~1MW
Location	Public area	Charging station, Highway corridor	Fleet charging, utility vehicle
Charging power block	3Φ, 10~15kW	3Φ, 20, 30, 40, 50kW, 60kW	50kW,60kW 100kW, 120kW
			





DESIGN TRENDS AND THE SPECS

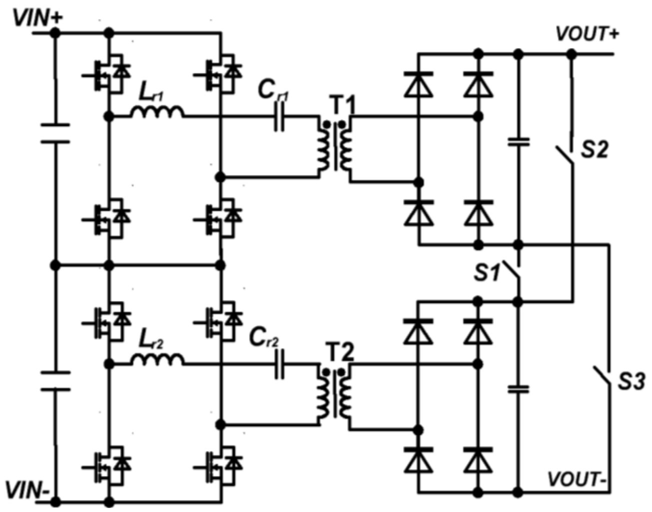


Description	Specifications
DC Input Voltage	650Vdc - 870Vdc
DC Output Voltage	200V-1000V
CP Range	300V-1000V
Output Power	60kW
Efficiency	98.5% Peak

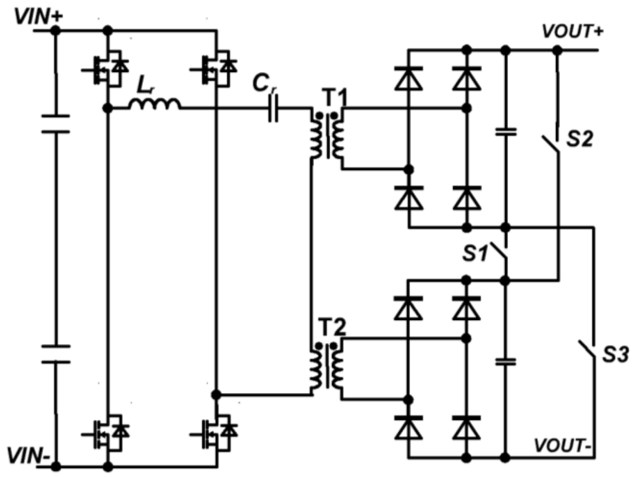
- Wide output voltage range to cover all types of Evs.
- High power rating for lower $/W: 30kW, 40kW → 50kW, 60kW, 100kW, 120kW
- High efficiency, high power density and low cost

TOPOLOGY SELECTION

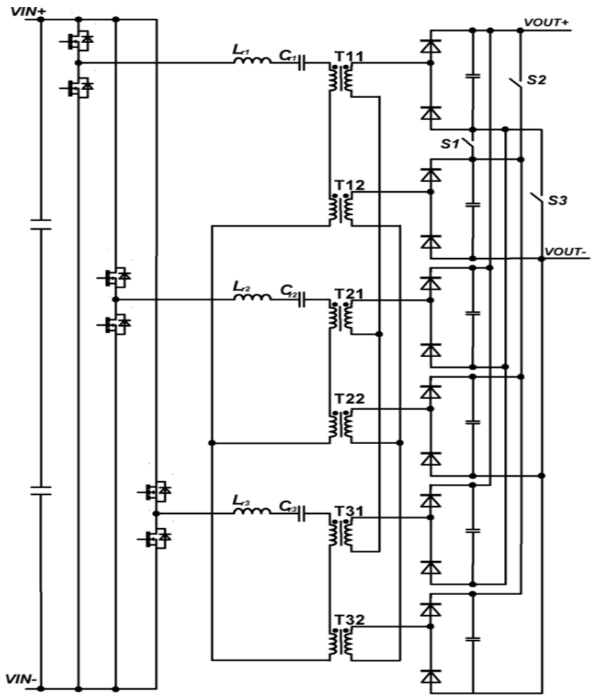
Si Solution
600V devices



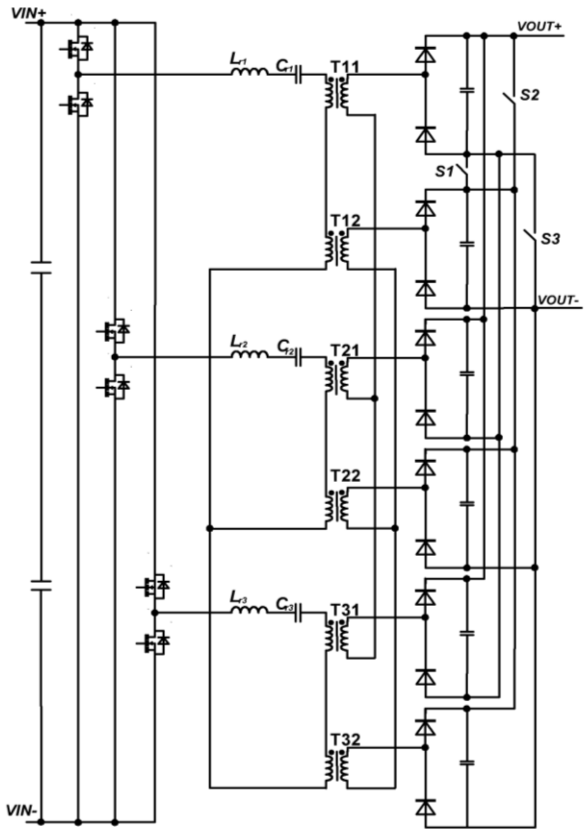
SiC 2 level solution
1200V devices



30kW-60kW & above
SiC Solution 1200V devices

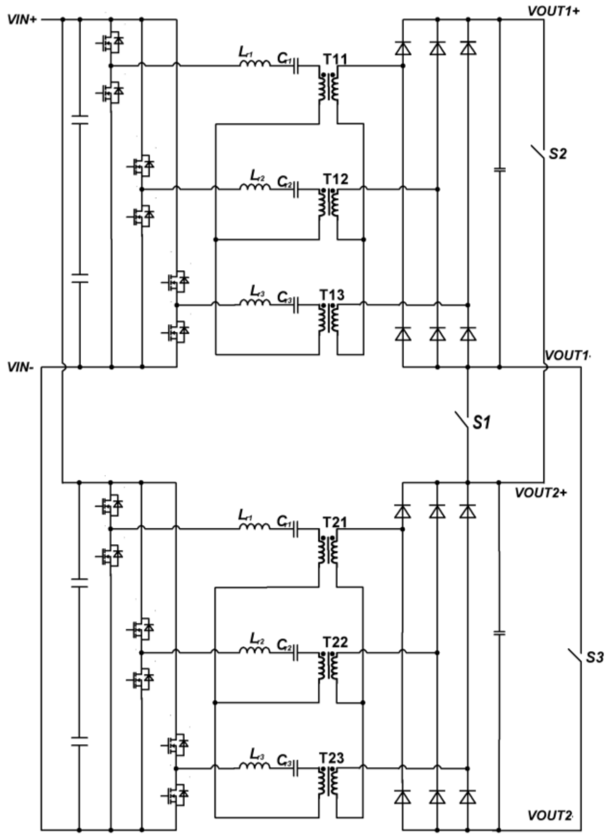


SINGLE CONVERTER VS. TWO CONVERTERS



Single converter

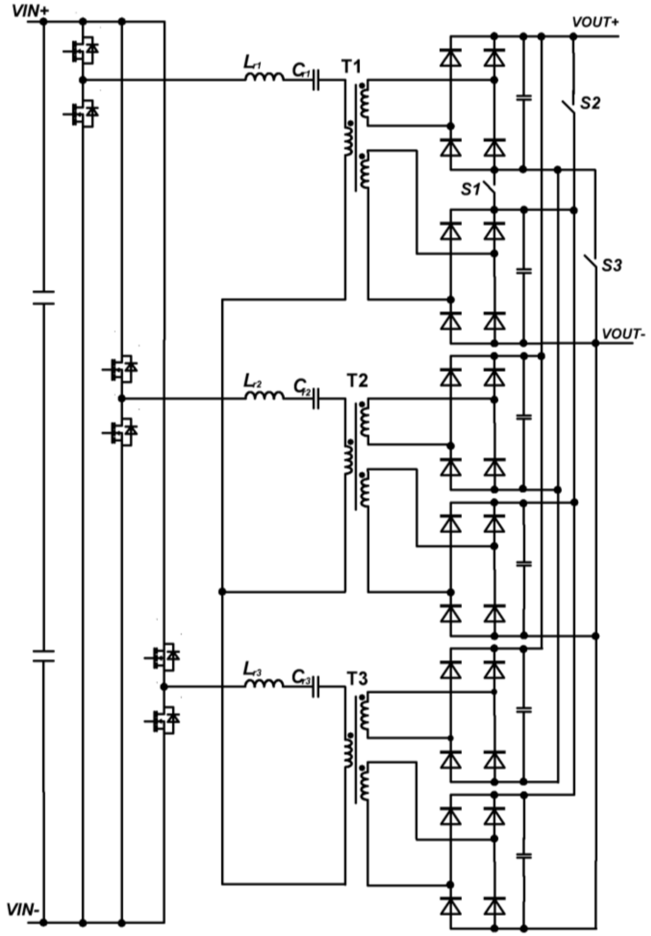
	Single Converter	Two Converters
Primary MOSFET	12	12
Gate Drive	6	12
Transformers	6	6
Resonant Chokes	3	6
Resonant Cap	1 set	2 sets
# of Primary Current Sensor	3	6
# of Output current Sensor	1	2 or 3
Control	Simple	Complex • 6 PWM outputs • Current sharing
Total relative cost	Low	High
Power density	High	Low



Two converters

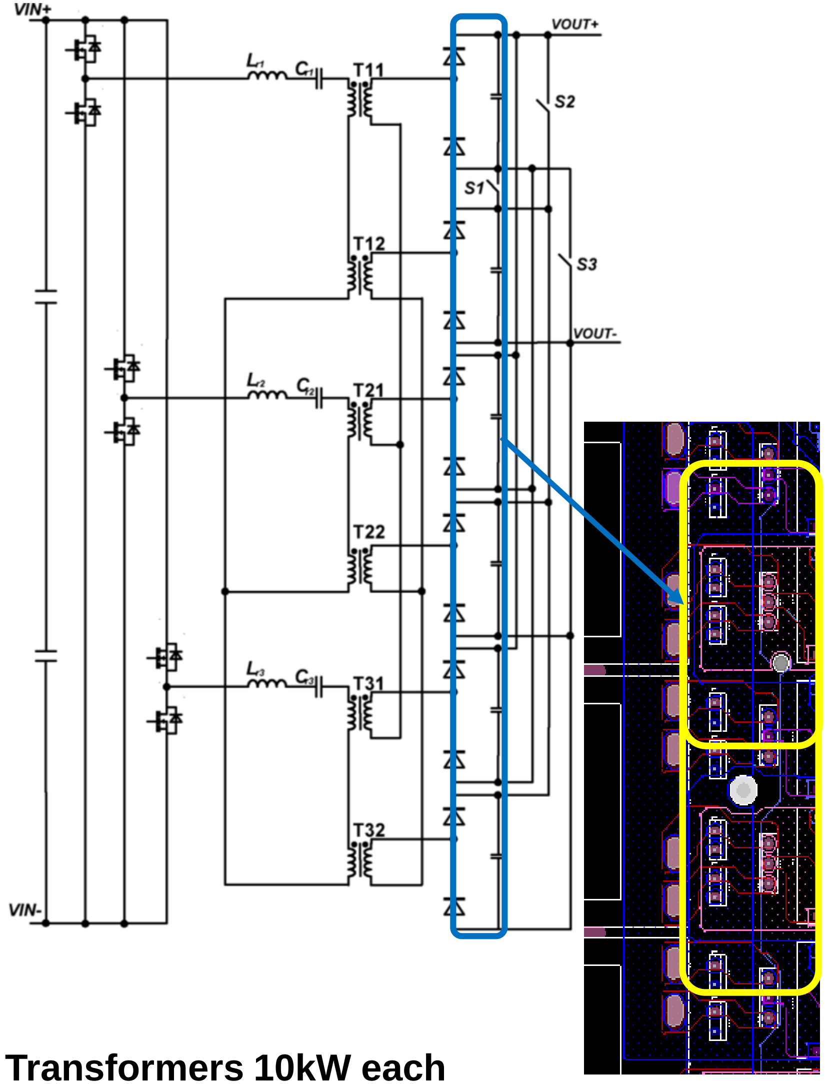
Compared to the two converters solution, the overall cost of single converter is lower. The control is simple. The challenges are on the current sharing and voltage sharing.

TRANSFORMER AND OUTPUT RECTIFIER



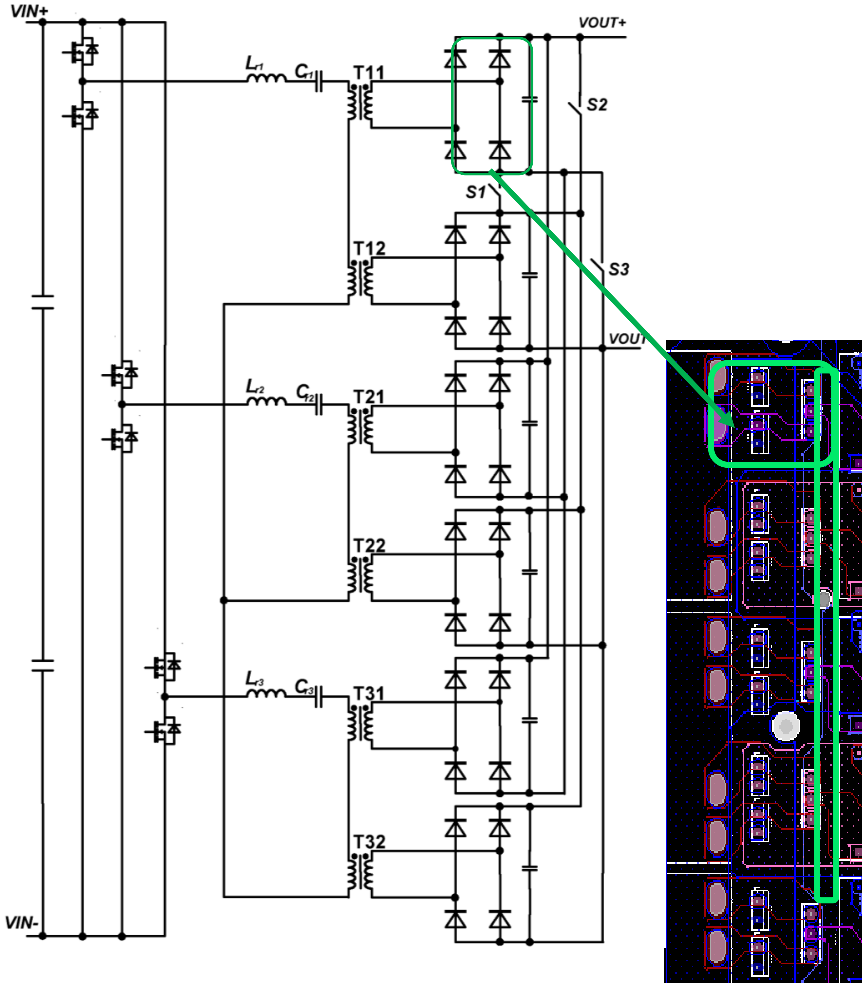
3 Transformers 20kW each

- Full Bridge output rectifier
- Voltage/current sharing concerns
- Thermal Risk on transformer



6 Transformers 10kW each

- Half Bridge output rectifier
- Large current commutation loop. EMI concern
- Voltage sharing concerns in series mode



6 Transformers 10kW each

- Full Bridge output rectifier for small commutation loop
- Voltage sharing concerns in series mode

FACTORS ON THE OUTPUT VOLTAGE SHARING – TX COUPLING

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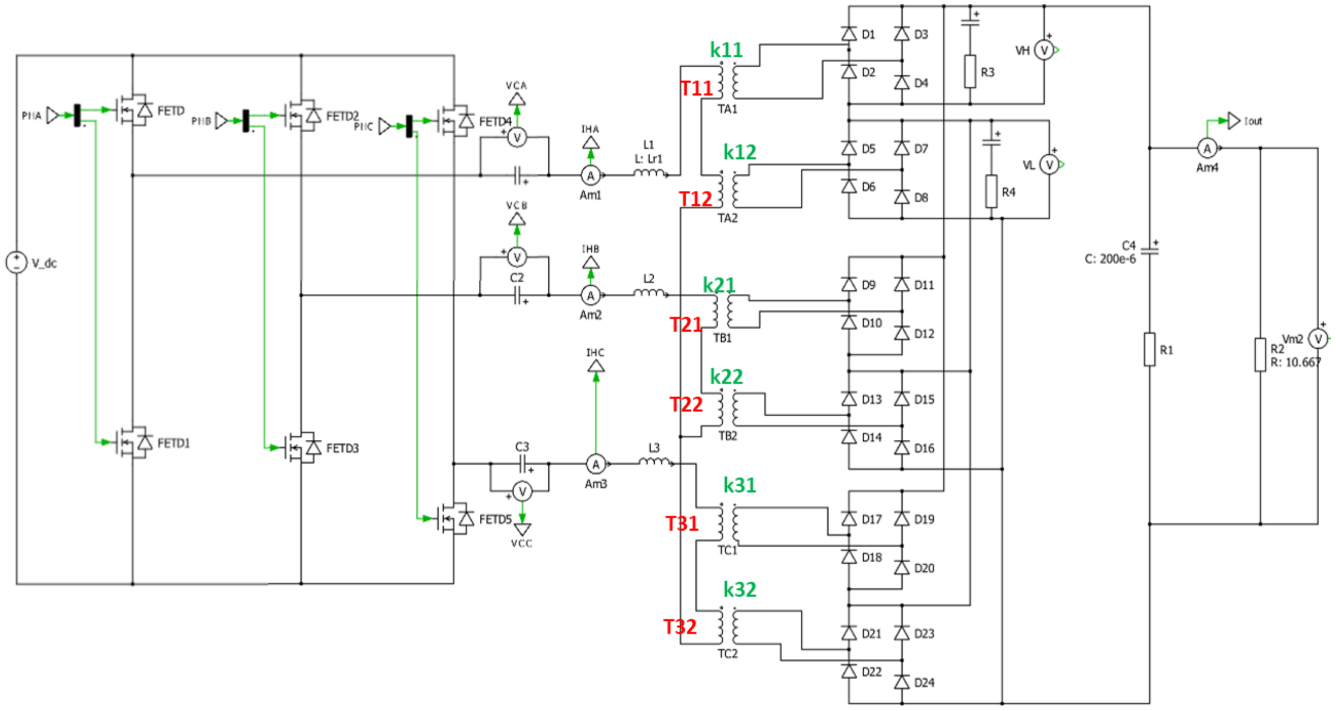
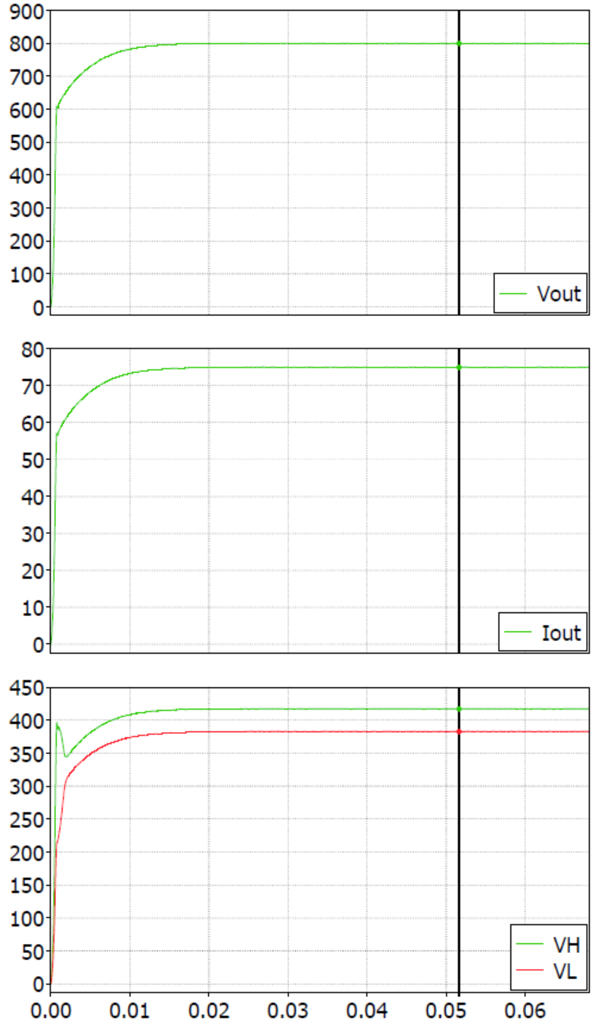




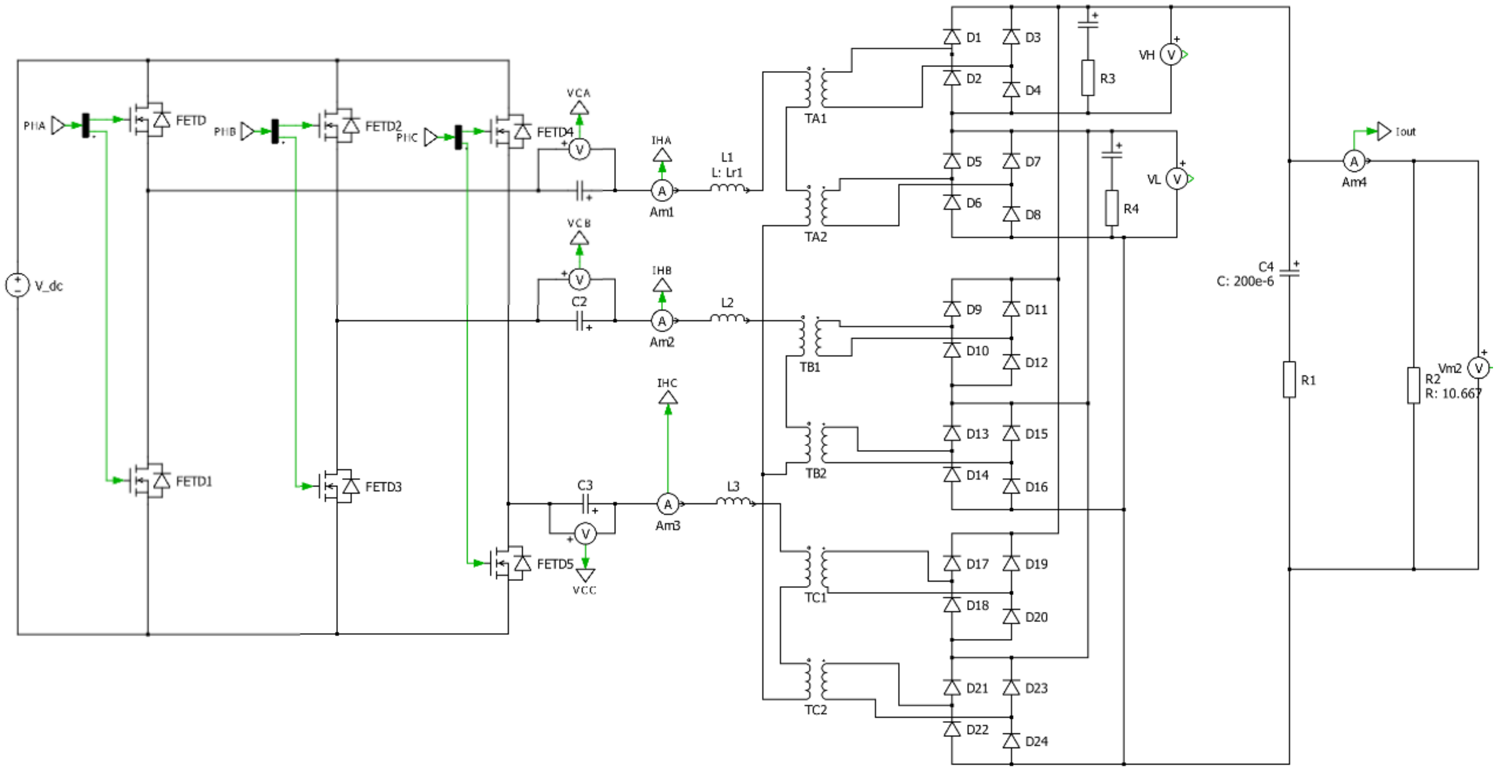
- The tolerance of Vf – too small compared to the output voltage
- The parasitic inductance at secondary. – Addressed by PCB layout
- The coupling of the transformer can vary from 0.97 to 0.99
- 0.99 for the high side and 0.97 for the low side in the simulation.
- For 800V output in series mode, the voltage difference between two outputs is 34V

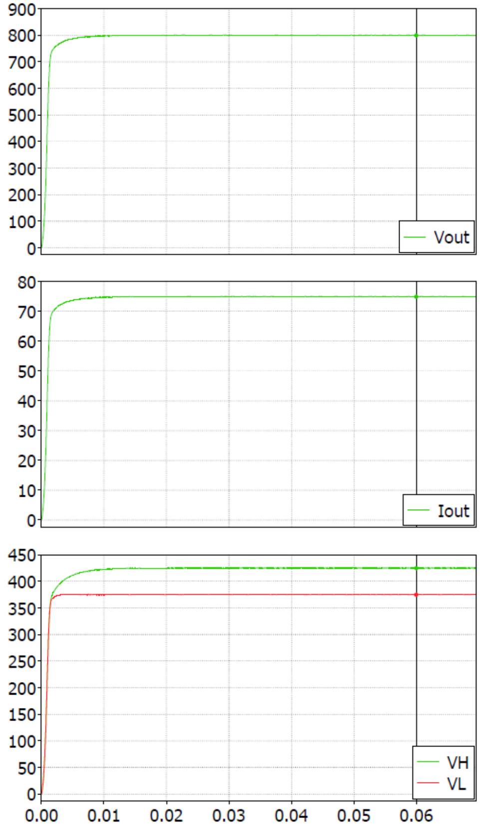
k11 = k21 = k31 = 0.99

k12 = k22= k32 = 0.97

$\Delta V = V_H - V_L$ = 417V-383V = **34V**

FACTORS ON THE OUTPUT VOLTAGE SHARING - MAGNETIC INDUCTANCE





- Lm = 15uH with tolerance ± 7%
- At the upper limit for the high side and lower limit for the low side
- The voltage difference between two outputs can be up to 50V for 800V output.

$L_{m\_TA1} = L_{m\_TB1} = L_{m\_TC1}$ = 16.05uH

$L_{m\_TA2} = L_{m\_TB2} = L_{m\_TC2}$ = 13.95uH

$\Delta V = V_H - V_L$ = 424V-374V = **50V**

OUTPUT VOLTAGE SHARING – SIMULATION AND TEST RESULTS

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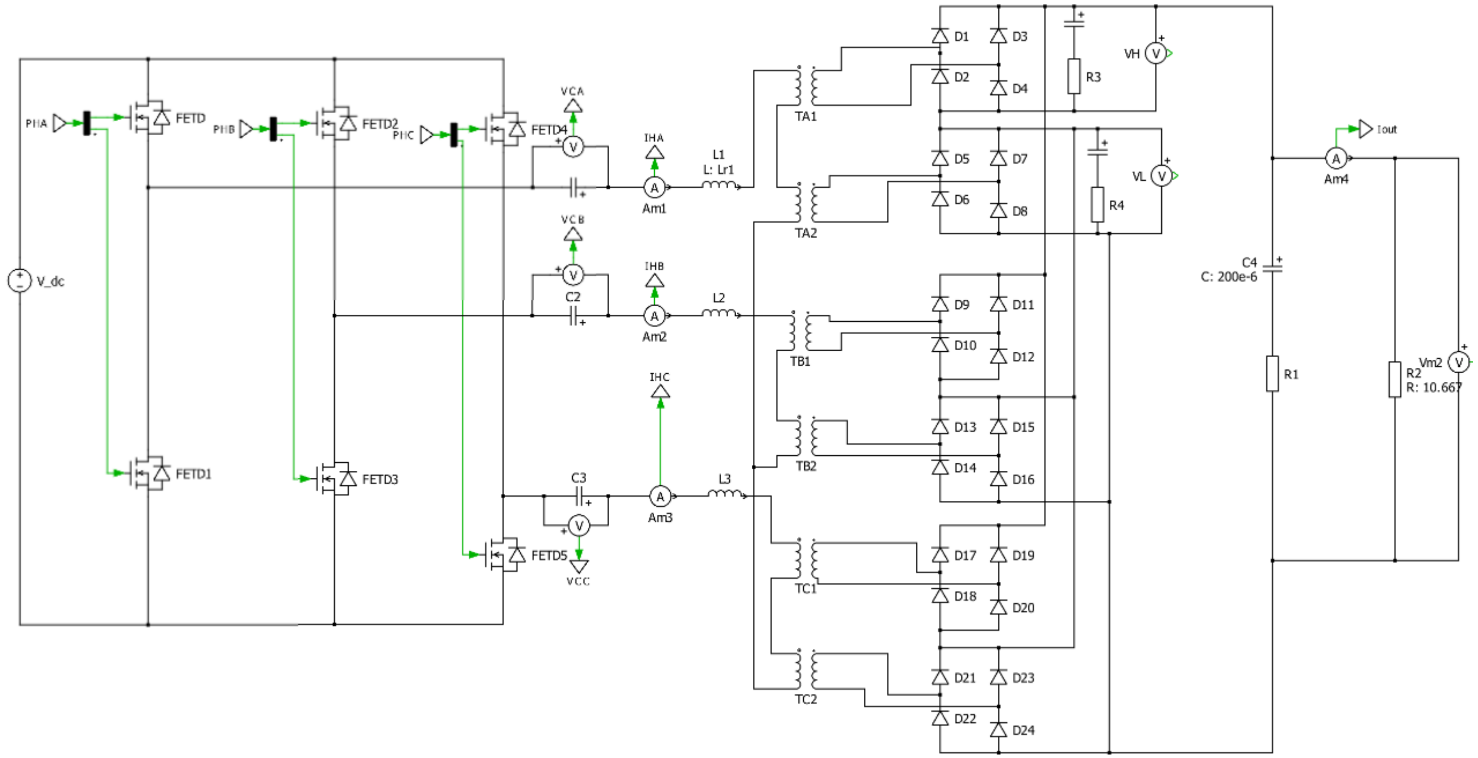
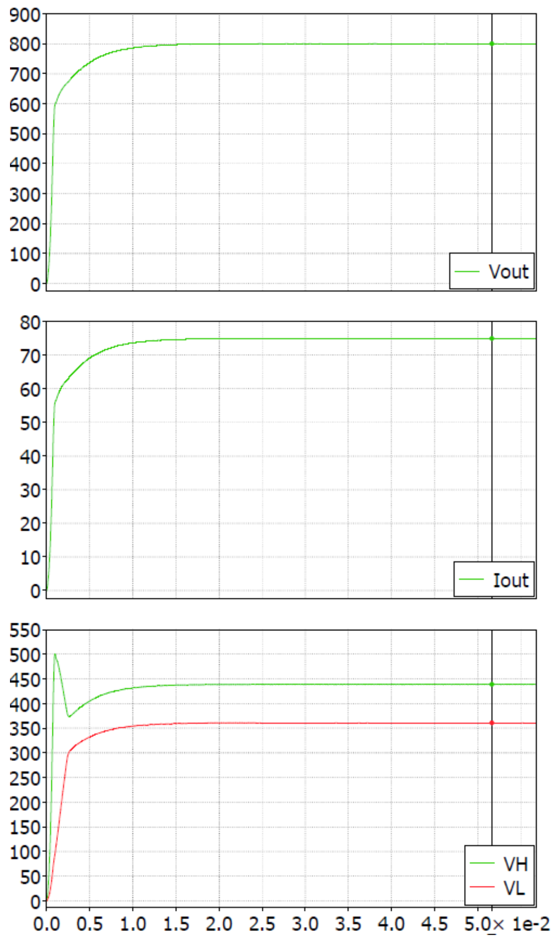




- The coupling of the transformer varies from 0.97 to 0.99
- Lm = 15uH with tolerance ± 7%
- Transformers are connected in series for both primary and secondary
- The voltage difference between two outputs is 78V.

Test result			
Output	Load	VH	VL
500V	20%	240V	262V
	50%	228.6V	271.9V
	100%	222.3V	278.6V
800V	20%	383.6V	416.9V
	50%	377V	422.7V
	100%	364.7V	435.3V

71V difference!

k11 = k21 = k31 = 0.99

k12 = k22= k32 = 0.97

$L_{m\_TA1} = L_{m\_TB1} = L_{m\_TC1} = 16.05uH$

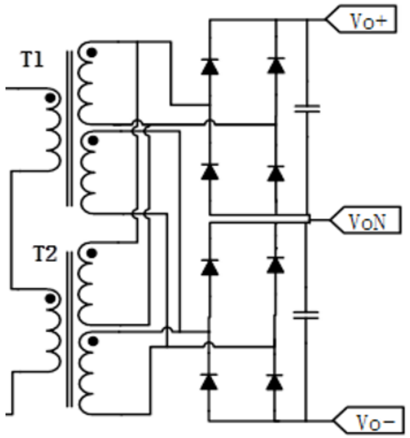
$L_{m\_TA2} = L_{m\_TB2} = L_{m\_TC2} = 13.95uH$

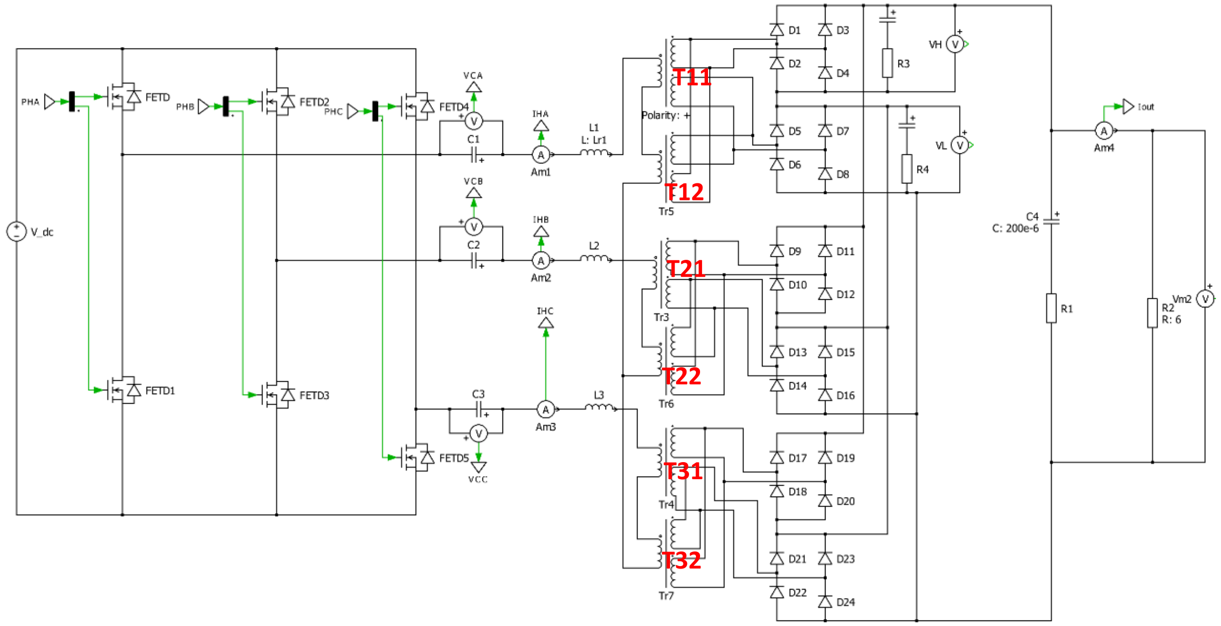
$\Delta V = V_H - V_L = 439V\text{-}361V = \mathbf{78V}$

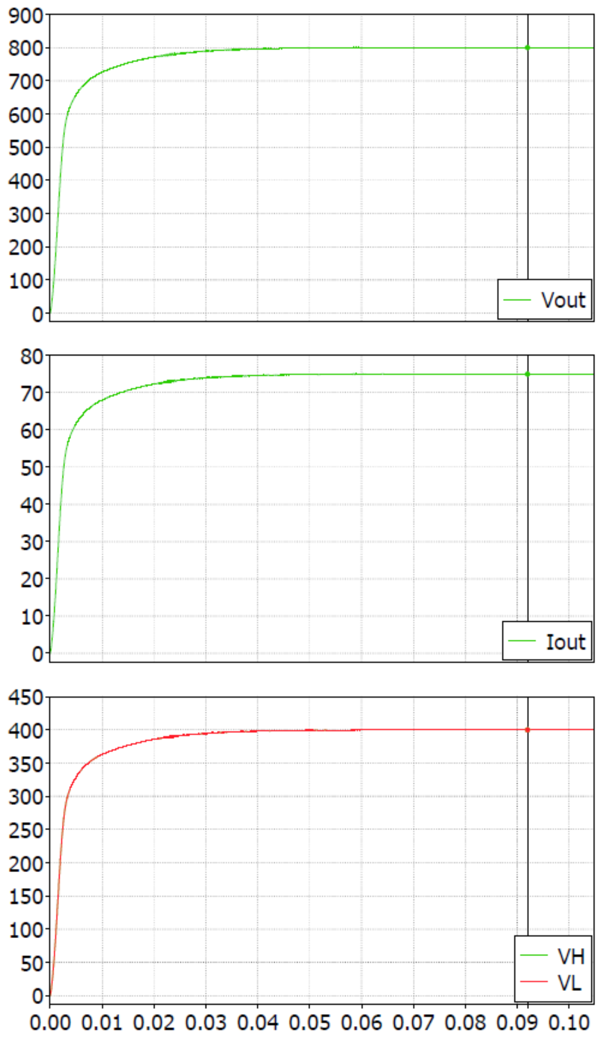
PROPOSED SOLUTION AND SIMULATION RESULTS

The proposed transformer design with special winding coupling is shown here.
Refer to the simulation results, the voltage balance between two outputs can be achieved even with the tolerance of the transformers.

- The coupling of the transformer varies from 0.97 to 0.99
- Lm = 15uH with tolerance ± 7%







TEST RESULTS WITH THE PROPOSED SOLUTION

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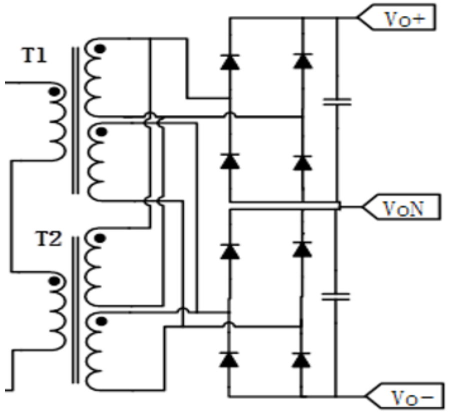
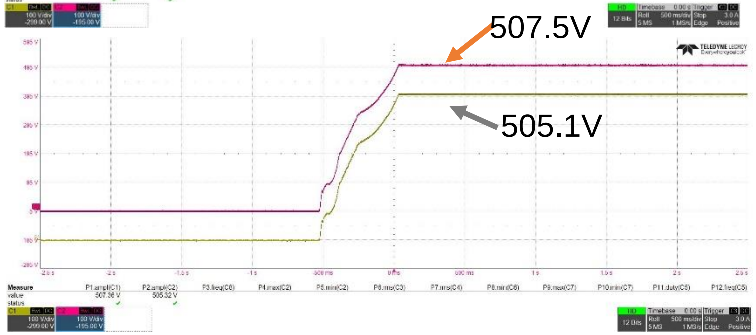


Test result			
Output	Load	VH	VL
500V	20%	250V	249.8V
	50%	250V	250V
	100%	253.1V	253.8V
800V	20%	401.7V	400.4V
	50%	403.2V	402.1V
	100%	404.5V	406.1V
1000V	20%	506.8V	505.7V
	50%	506.3V	505.5V
	100%	507.5V	505.1V

Test result 500V output
100% load

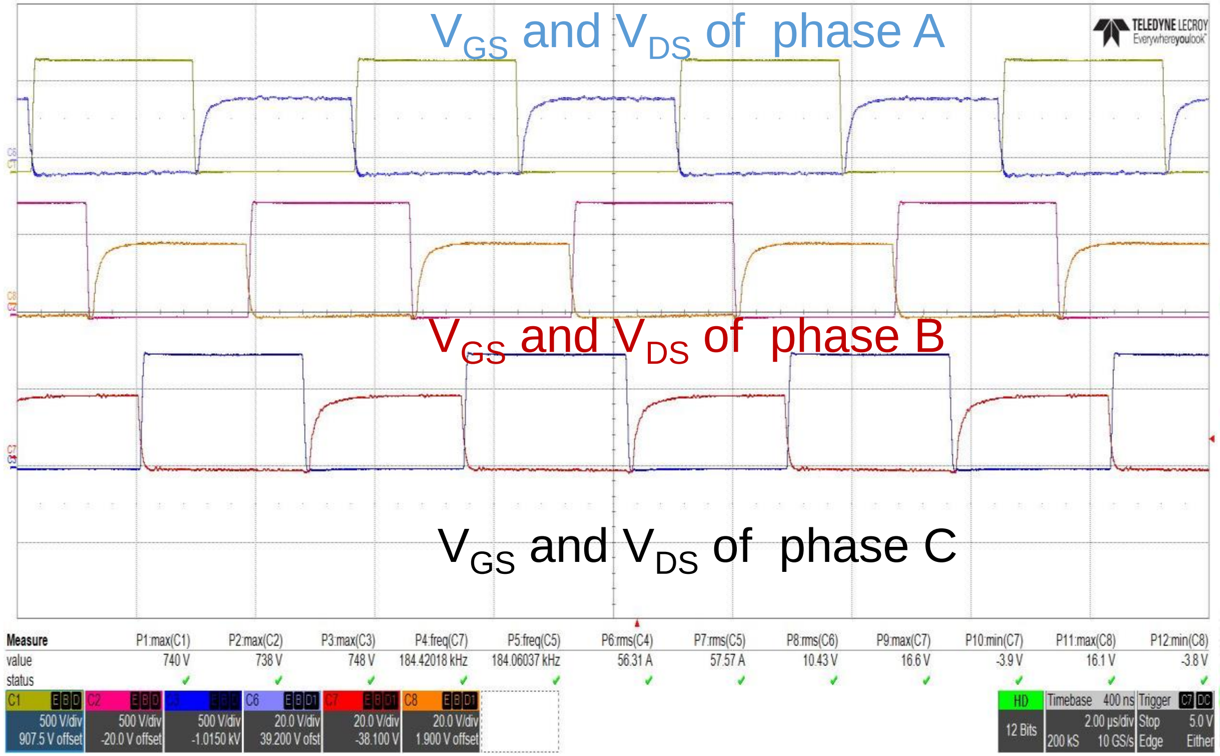
Test result 800V output
100% load

Test result 1000V output
100% load

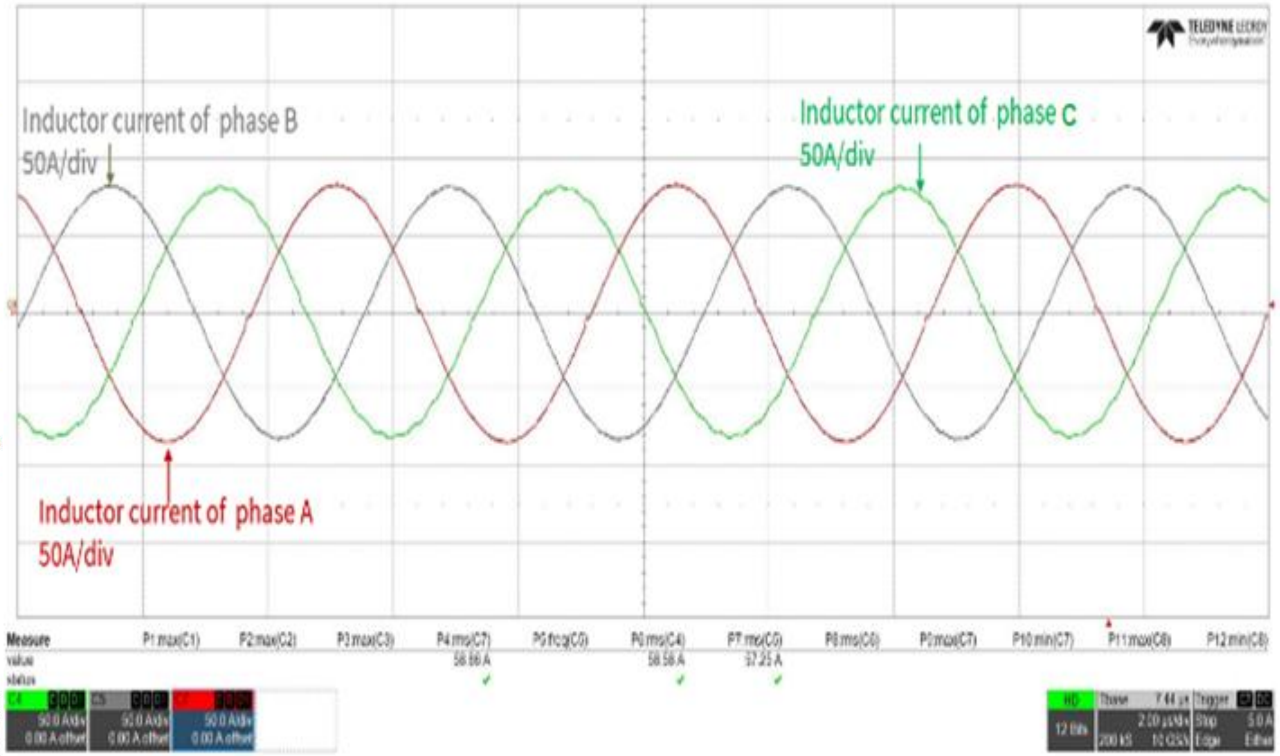


The Proposed solution works for both transient and steady operation mode.

WAVEFORMS



VGS and VDS of phase A
VGS and VDS of phase B
VGS and VDS of phase C
TELEDYNE LECROY
Measure P1:max(C1) P2:max(C2) P3:max(C3) P4:freq(C7) P5:freq(C5) P6:rms(C4) P7:rms(C5) P8:rms(C6) P9:max(C7) P10:min(C7) P11:max(C8) P12:min(C8)
value 740 V 738 V 748 V 184.42018 kHz 184.06037 kHz 56.31 A 57.57 A 10.43 V 16.6 V -3.9 V 16.1 V -3.8 V
status
C1 500 V/div 907.5 V offset
C2 500 V/div -20.0 V offset
500 V/div -1.0150 kV
C6 20.0 V/div 39.200 V ofst
C7 20.0 V/div -38.100 V
C8 20.0 V/div 1.900 V offset
HD 12 Bits
Timebase 400 ns 2.00 µs/div 200 kS 10 GS/s
Trigger Stop 5.0 V Edge Either



Inductor current of phase B
50A/div
Inductor current of phase C
50A/div
Inductor current of phase A
50A/div
Measure
value
status

EFFICIENCY TEST RESULTS

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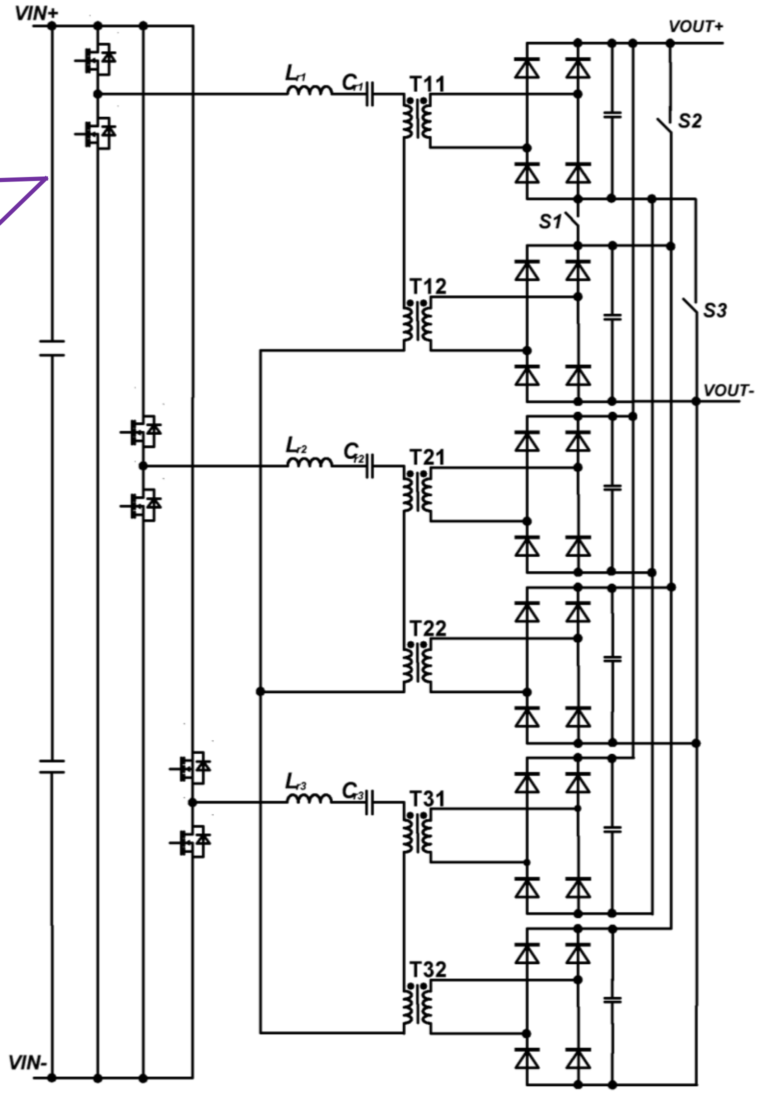
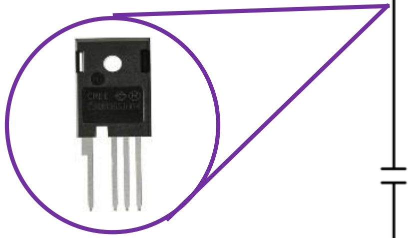
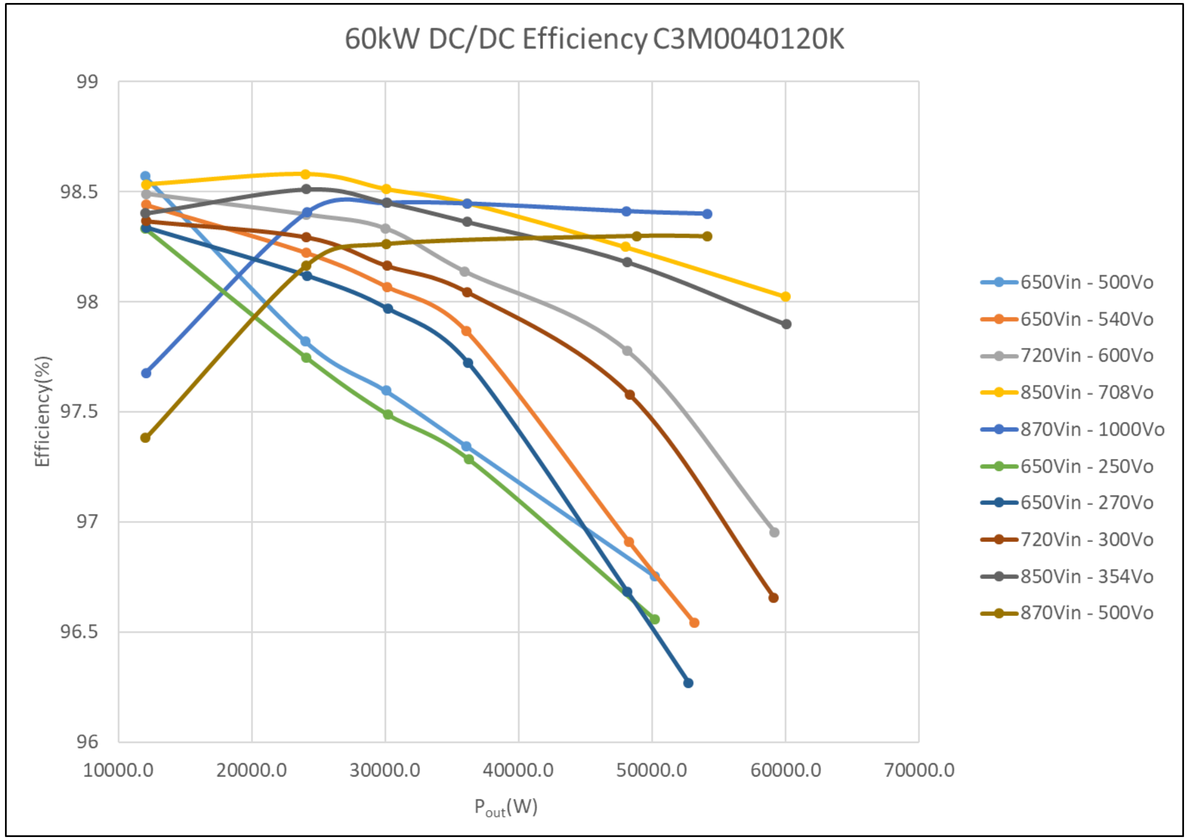




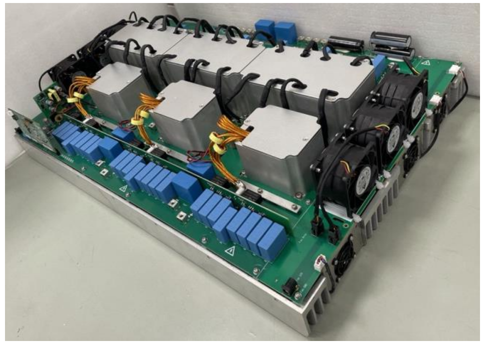
1200V 40 mohm
SiC MOSFET
X 12

32mohm, 21mohm
for higher efficiency



SUMMARY

A novel transformer design is proposed to optimize the voltage balance to support a cost-effective design of the DC/DC stage for EV fast charger. Both the simulation and test results show very good voltage balance. Thanks to the low power loss of Wolfspeed C3M SiC MOSFET, with the proposed solution, with proper PCB layout, all the design targets are achieved.



- ✓ High Efficiency High Power Density
- ✓ Wide voltage range 200Vdc-1000Vdc
- ✓ Good Current Sharing between three phases
- ✓ Simple control, good voltage sharing between outputs
- ✓ Low parts counts, 60kW is achieved based on discrete SiC MOSFETs

THANK YOU!