Analysis of the Thermal Management Performance Of the TDK 12V DC-DC Converter Used in the Nissan X-Trail Hybrid

Purpose：
To analyze the TDK-manufactured 12V DC-DC converter, from the viewpoint of the thermal management, to asses the heat removal performance. The temperature of critical devices and components is computed and compared with specifications.

Analyzed system：
12V Output DC-DC converter
(DAA-HNT32、2015 model)
Converter ASSY DCDC(292A0-4BC0A)

Contents:

1. Executive Summary

In this report, the thermal management characteristics of the TDK-manufactured 12 DC-DC Converter used in the NISSAN XTRAIL Hybrid automotive is analyzed. The analysis aims (1) to extract and equivalent thermal network (TN) that will allow estimation of the temperature of critical devices and components, and (2) analyze the construction of the system.

The thermal analysis and extraction/estimation of the effective thermal resistances is carried out by:

- Actual hardware dimensions measurements (See Report 15H-0694-1)
- Circuit SPICE simulation for determining heat generation sources
- Analytical modeling (heat sink, components thermal models)
- Thermal simulation.

Results:

1. The 12V DC-DC converter is mounted on the Li-ion battery pack and housed in an aluminum case with extruded fin heat sink (Fig 5, p.8)
2. The whole DC-DC converter is air cooled by a blower fan and ducted heat sink (Fig.4, p.7)
3. The main heat generation sources are (1) Rectifier diodes (PD~64W at full load), and (2) the Full Bridge switching transistors (PB~28W at full load). This condition results in diode junction temperature Tj~160°C (Spec Tjmax=175°C)
4. The ducted fin-heat sink has Rth~1.4°C/W in natural convection, and Rth~0.4°C/W in forced convection mode with air flow speed of Vf=4m/s (estimated)
5. This level of air flow seems to be necessary in order to prevent device overheating.
6. The rectifier's diodes junction-to-heat sink thermal resistance seems to be constrained by the PCB via thermal resistance. It seems feasible to reduce this effect by increasing the number of thermal vias in the PCB Cu pads.
7. The maximum temperature in the PCB occurs at the mounting position of the rectifier diodes (Tpcb_diode~=153°C). This value is higher than the allowable maximum operating temperature of conventional FR4 material (130°C). Therefore, it is expected that a high-Tg (transition glass temperature) PCB is used.

2. Technology roadmap for the TDK-manufactured DC-DC converter

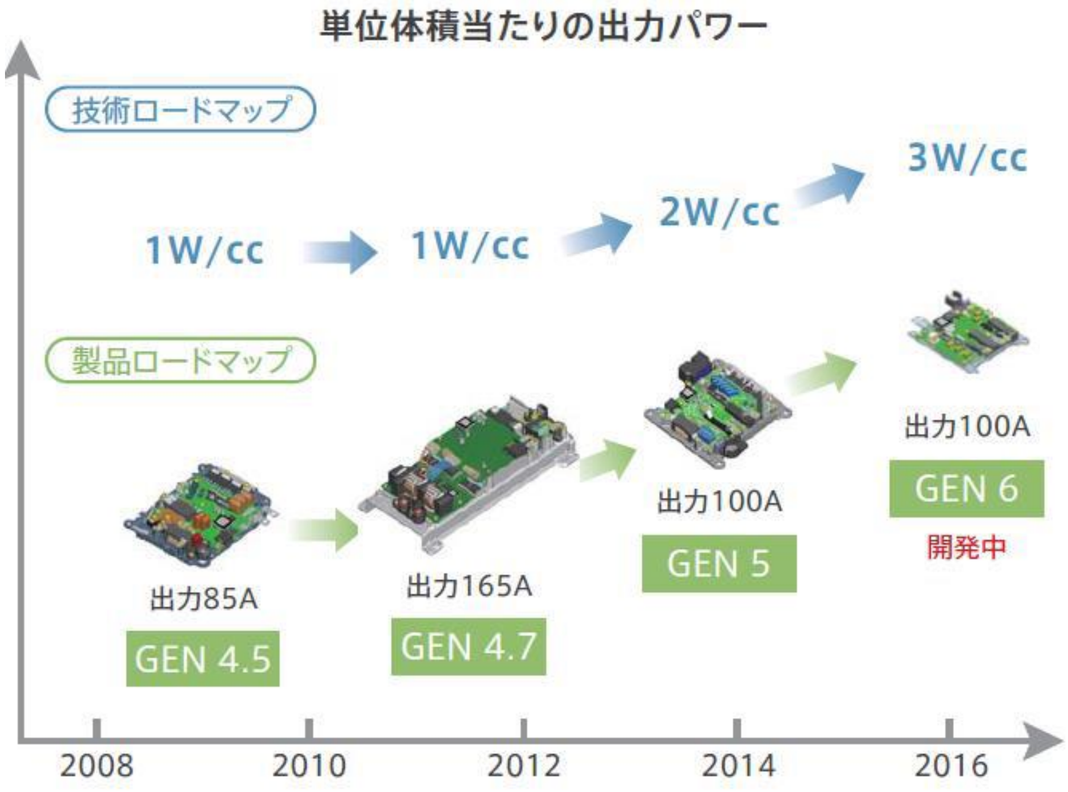
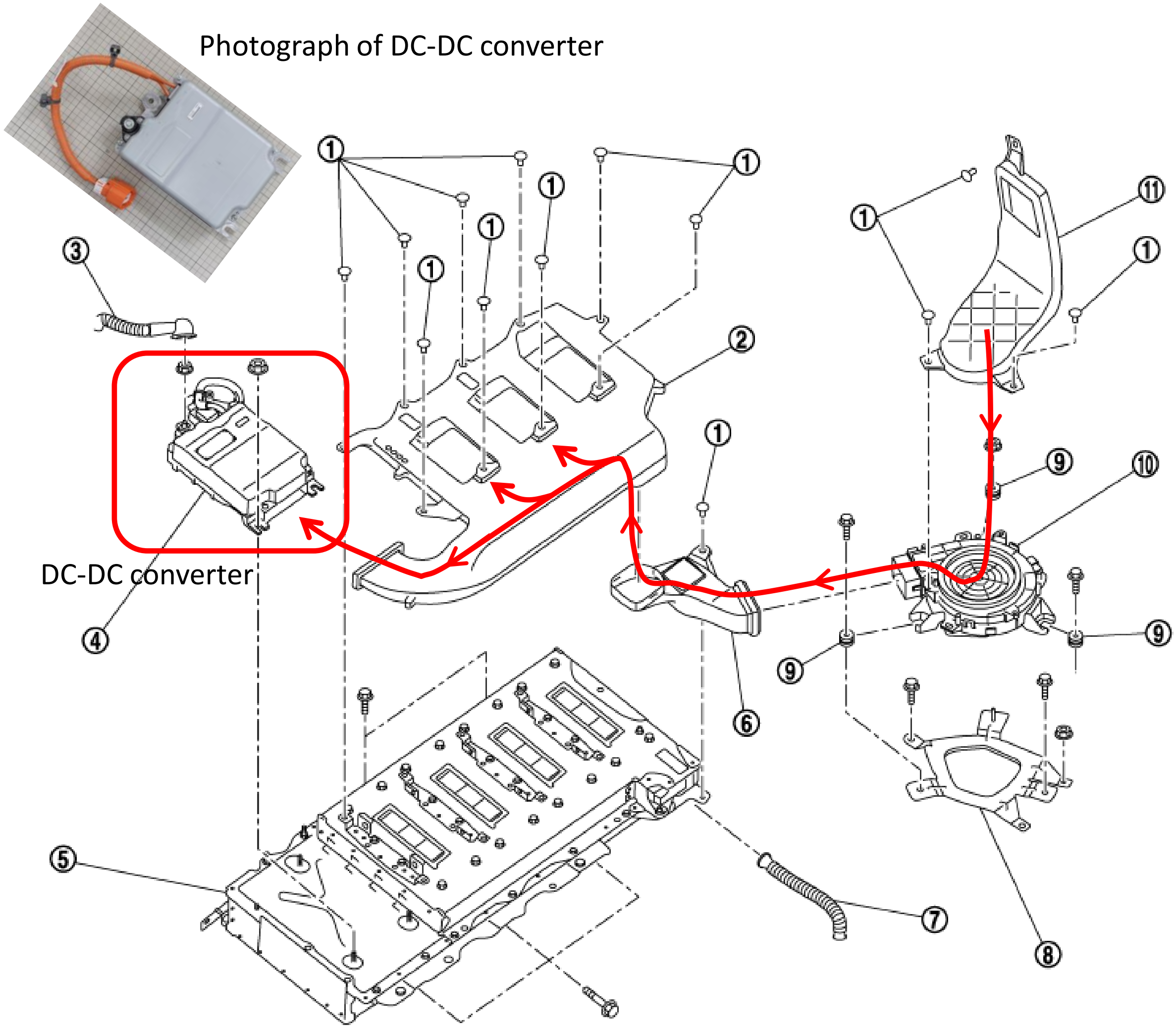
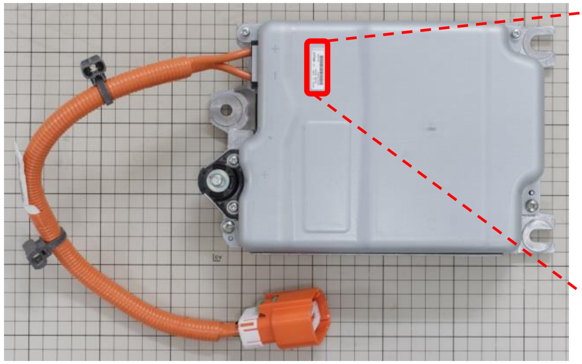


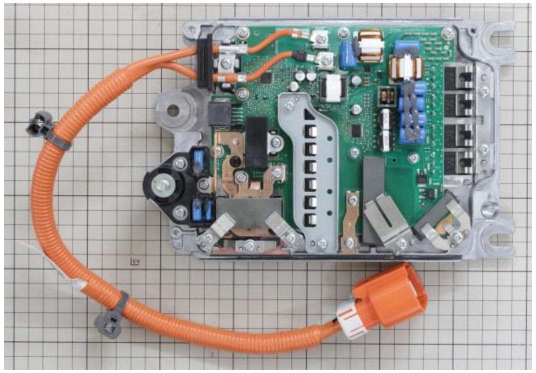
Fig.１：　Technology roadmap. GEN-5 is used in the Nissan X-TRAIL



2	Air duct 1
4	DC/DC コンバーター It converts the high voltage of the lithium-ion battery, and supplies the 12V battery.
5	Lithium-ion battery
6	Air duct 2
8	Battery cooling fan bracket
10	Battery cooling blower fan
11	Air duct 3

Fig.4 : Cooling system for Lithium-Ion battery
Airflow is distributed to the DC-DC converter by blower fan⑩ and duct ②.





Cover

Overall appearance

Fig.5：NISSAN　XTRAIL　TDK DC－DC Converter

TDK DC-DC Converter Case

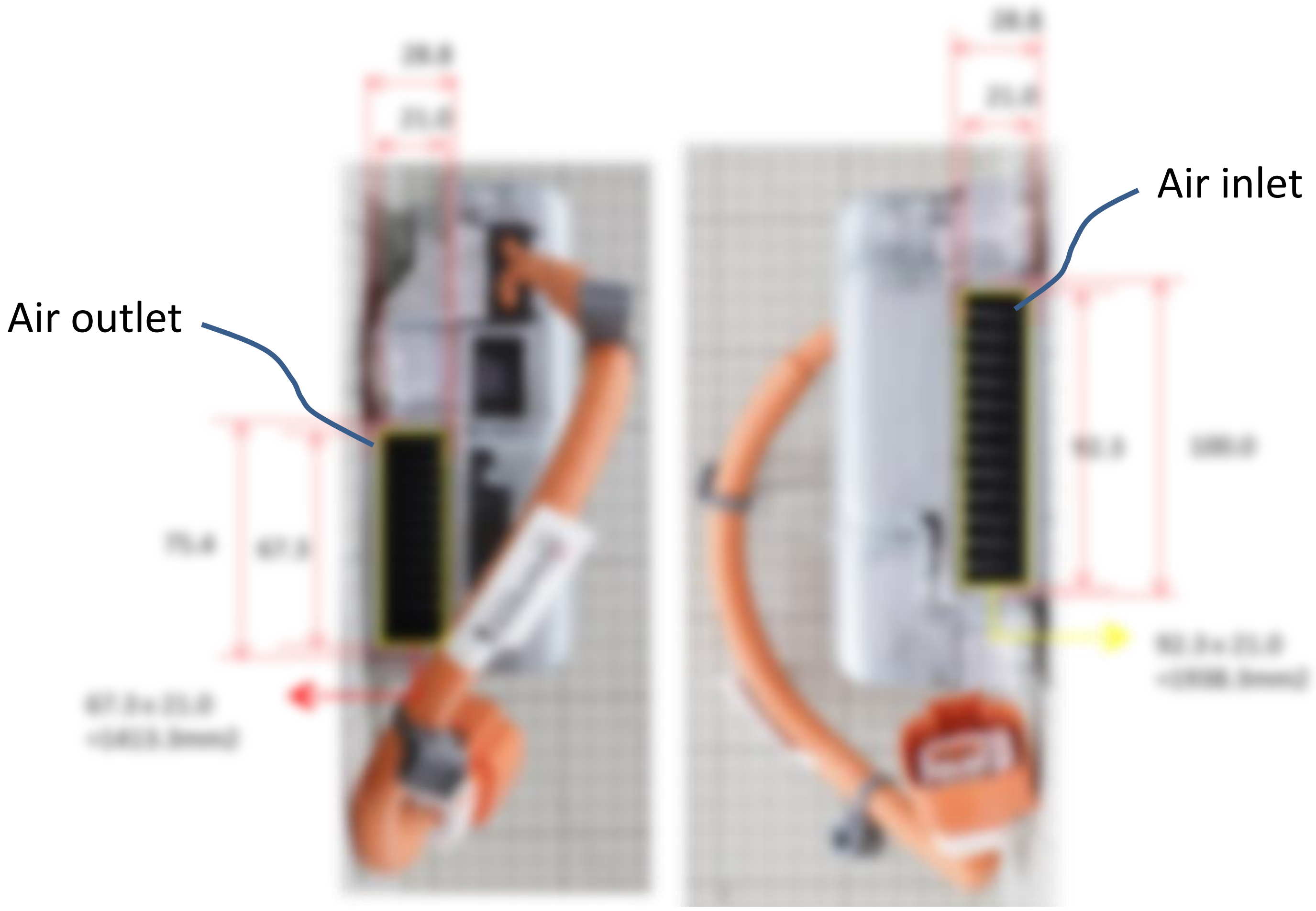


Fig.6：NISSAN　XTRAIL　TDK DC－DC Converter configuration
Air inlets for cooling

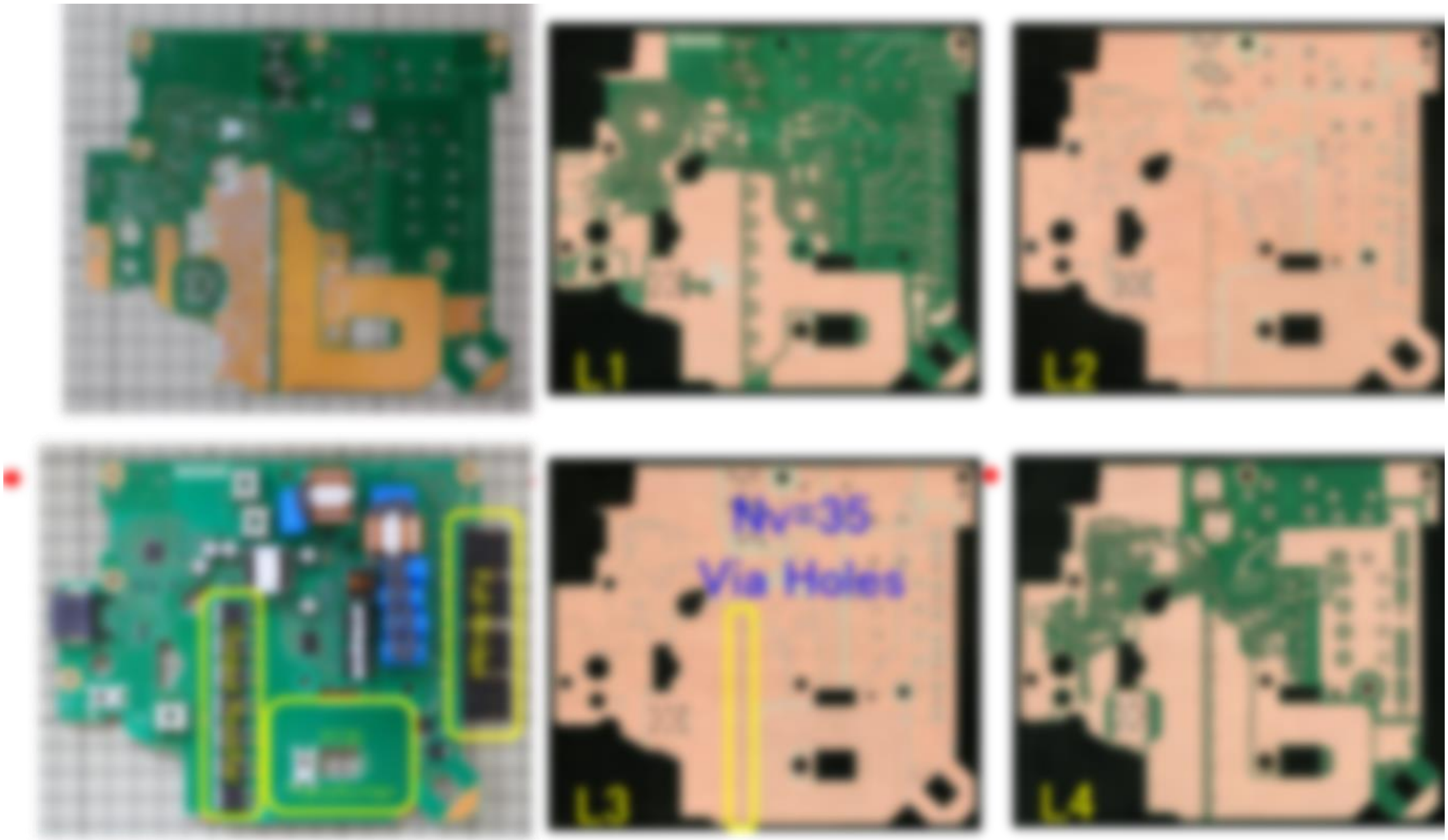


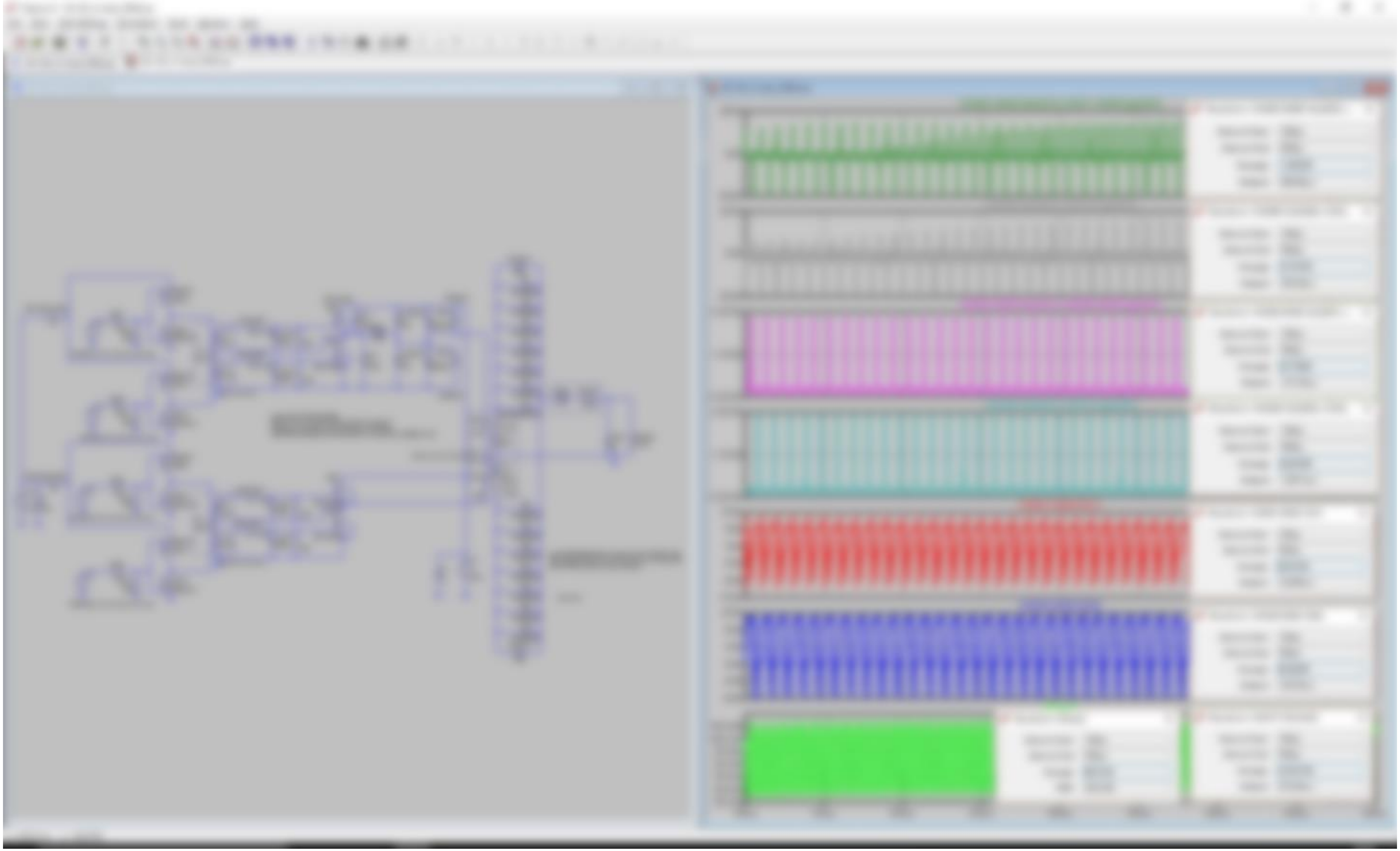
Fig.8：DC－DC Converter configuration
Images of each of the PCB Cu layers.

5. DC-DC converter :
Circuit block diagram and main heat generation sources.

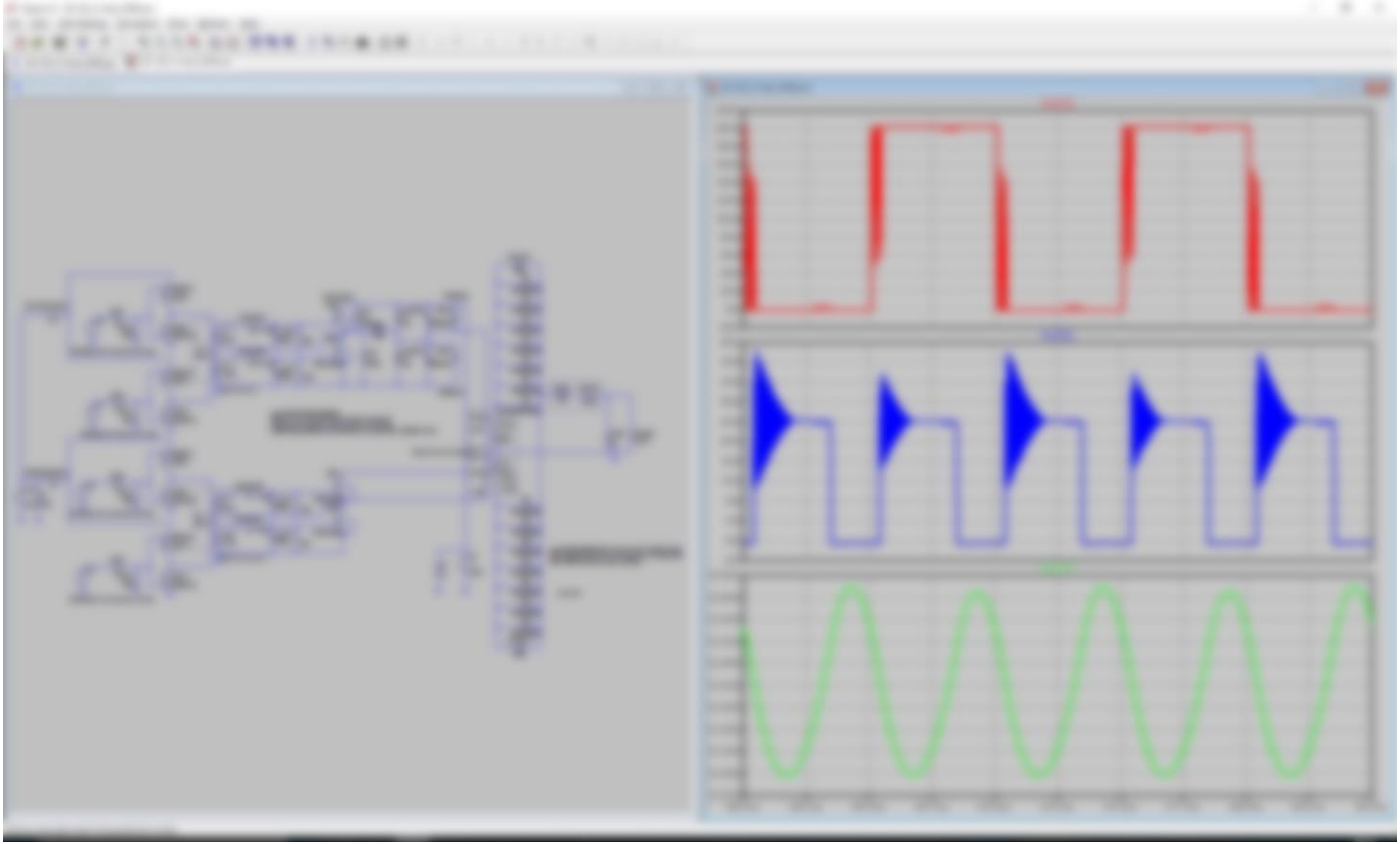
The main power loss and heat sources of the primary side
・Full-Bridge MOSFET （Q501~504）
・Transformer（TR802） + Shim inductance（L801）

The main power loss and heat source of the secondary side
・Rectifier diodes SBD（D184~191）
・Smoothing Coil（L2014）

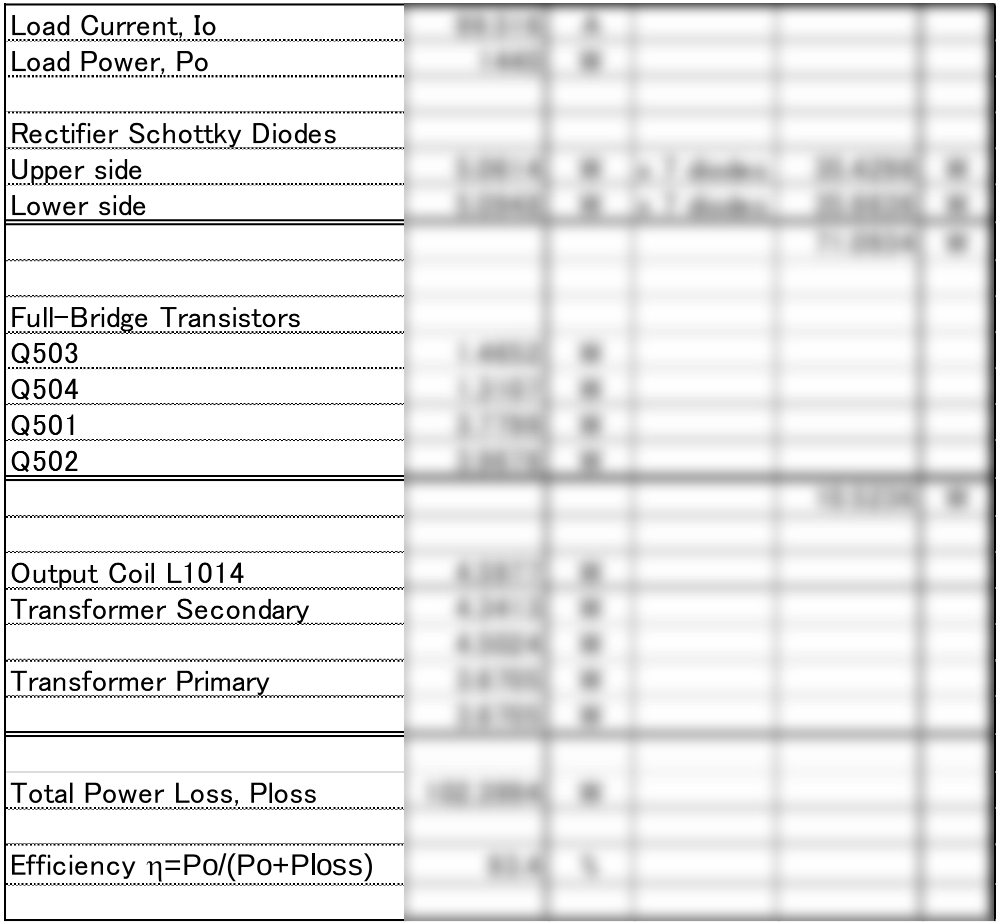
Fig.9 Block Diagram



SPICE simulation results of the power dissipated in (1) the Full-Bridge transistors, (2) the output rectifier diodes and (3) the output load.



SPICE simulation results of voltage waveforms



Load Current, Io	[redacted]
Load Power, Po	[redacted]
Rectifier Schottky Diodes	
Upper side	[redacted]
Lower side	[redacted]
	[redacted]
Full-Bridge Transistors	
Q503	[redacted]
Q504	[redacted]
Q501	[redacted]
Q502	[redacted]
	[redacted]
Output Coil L1014	[redacted]
Transformer Secondary	[redacted]
	[redacted]
Transformer Primary	[redacted]
	[redacted]
Total Power Loss, Ploss	[redacted]
Efficiency η=Po/(Po+Ploss)	[redacted]

Summary of SPICE simulated power losses in the DC-DC Converter.

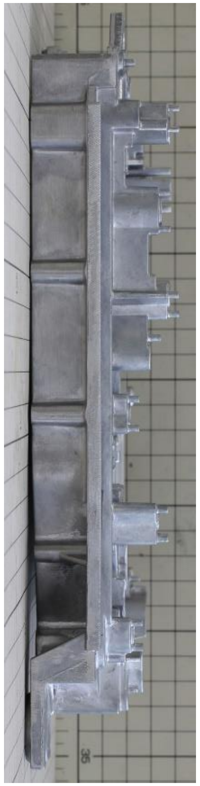
6. DC-DC converter: Heat sources and mounting to heat sink.

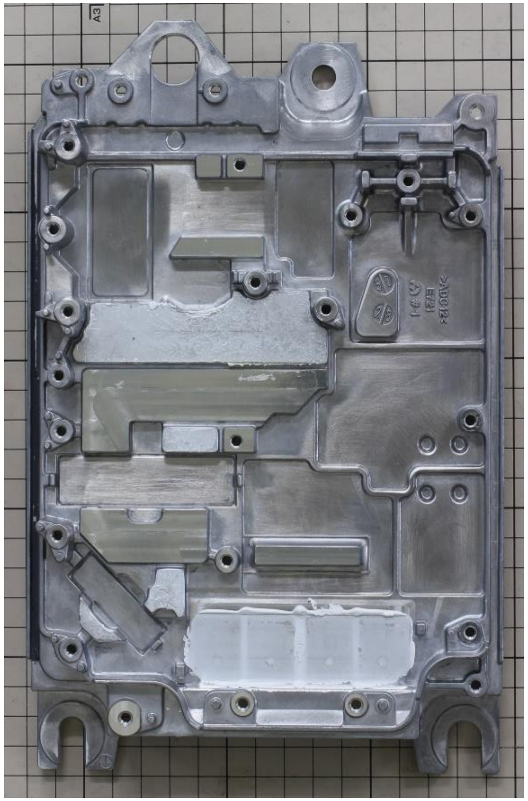
Device/Component	Tjmax [°C]	PKG	$R_{thj,c}$ [W/°C]	Mounting to the heat sink	$R_{thc,hs}$ [W/°C]
Full-Bridge Transistors STW75NF30	150[1)]	TO-247	[redacted]	[redacted]	[redacted]
Rectifier Schottky Diodes STPS41H100C-Y	175[1)]	D2PAK	[redacted]	[redacted]	[redacted]
Full-Bridge Transformer TR802 (Planar PCB transformer with partial ferrite core)	130[2)]		[redacted]	[redacted]	[redacted]
Smoothing coil L1014 (MB1H Ferrite core)	125		[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]	[redacted]

Notes：
1) From datasheet
2） Maximum allowable operating temperature for conventional FR4 laminate.

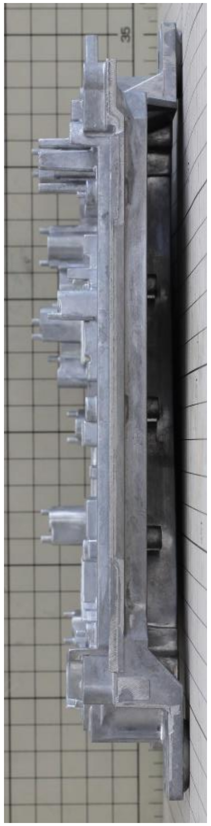
7.TDK DC-DC converter: Heat sink overview

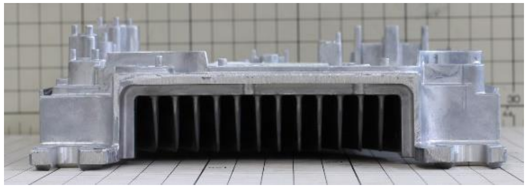
Fin side of the heat sink





PCB attachment side





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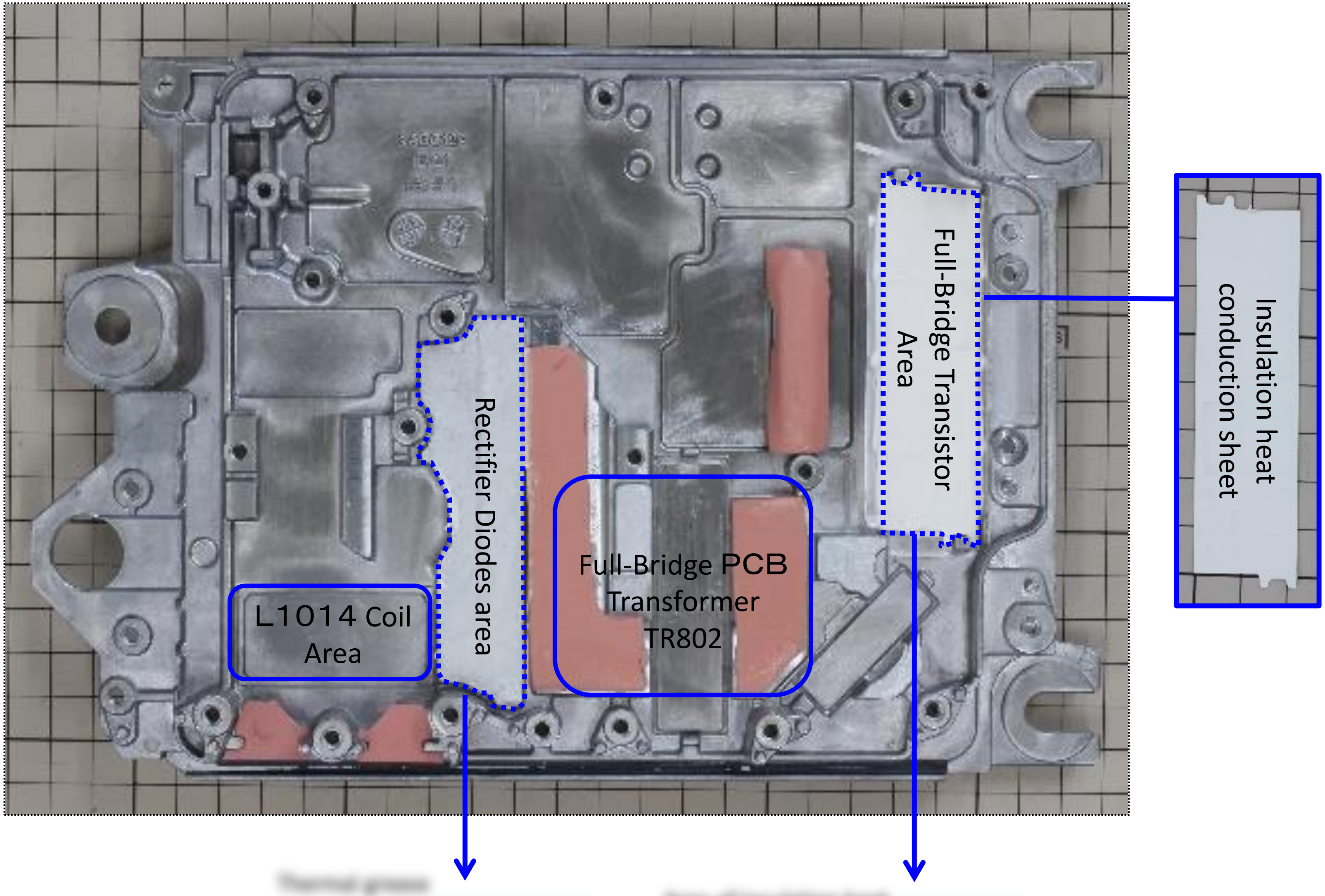
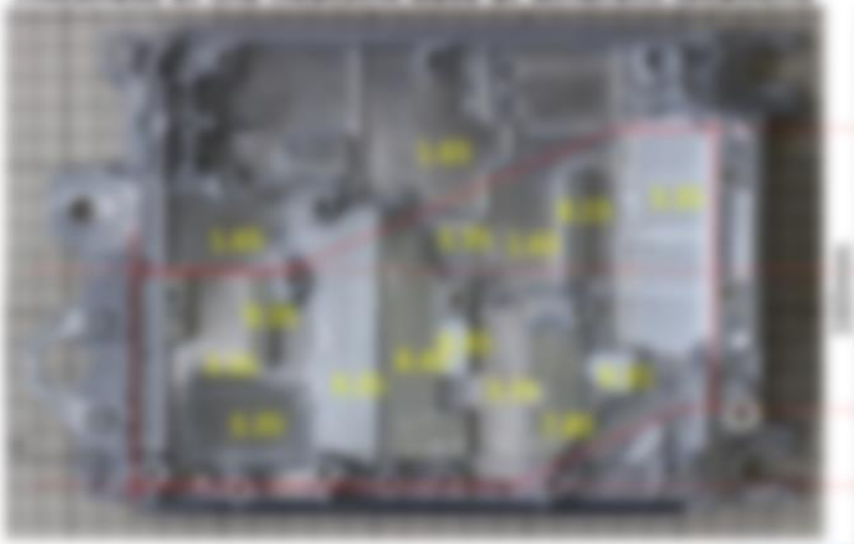


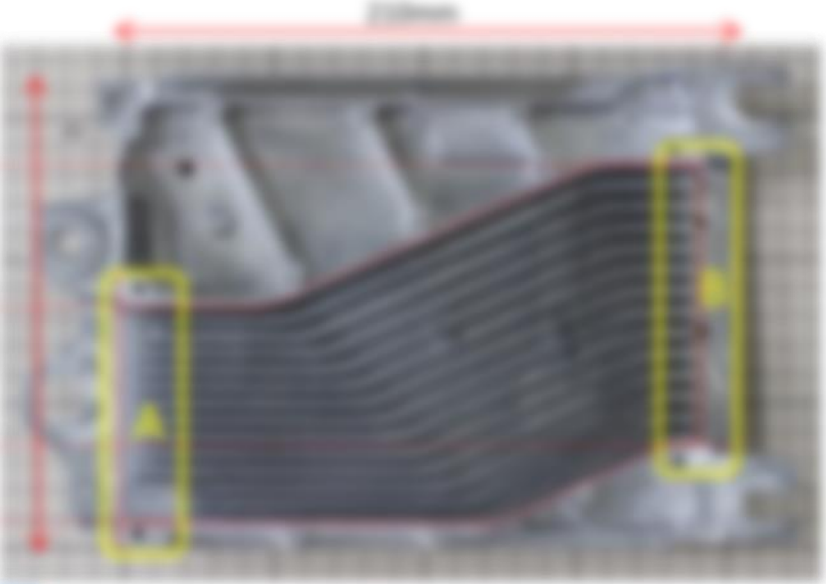
[redacted]

[redacted]

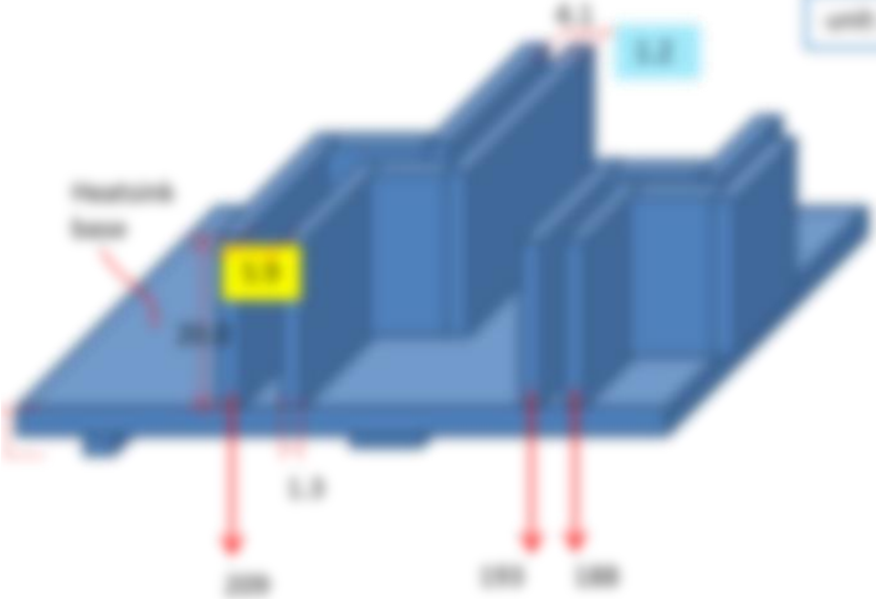
Heat source mounting area on the heat sink

Thickness of the heatsink base at different locations





unit: mm



Heat sink outline and dimensions

			A	B
H	Fin高さ	mm	20	20
t	Fin幅	mm	1.2	1.2
s	Fin-Fin間	mm	4.1	3.8
p	Finピッチ	mm	5.3	7.1
N	Number of Fins		14	14
W	Heatsink Fin area width	mm	88.8	92.3
L	Fin channel length (Avg)	mm	195	

8.TDK DC-DC Converter: Heat sink thermal resistance（1）

NISSAN XTRAIL HYBRID: 12V Battery DC-DC Converter

Heat Sink Dimensions

		Units	
	Heatsink material		[redacted]
Wb	Heatsink base width	mm	[redacted]
Lb	Heatsink base length	mm	[redacted]
Whs	Fin Heatsink width	mm	[redacted]
L	Fin Heatsink length	mm	[redacted]
Hf	Heatsink fin height	mm	[redacted]
t	Fin thickness	mm	[redacted]
p	Fin pitch	mm	[redacted]
s	Fin spacing s=p−t	mm	[redacted]
tb	Heatsink base thickness	mm	[redacted]
Afin	Heatsink Fin Area	mm2	[redacted]
Nfin,chan	Number of fin channels		[redacted]
Af	Total Fin Convection area	mm2	[redacted]
		cm2	[redacted]
Am	Fin profile area Am＝Lc x t	mm2	[redacted]
Abf	Area of Heatsink base for convection s･L･(Nfin−1)	mm2	[redacted]
Vhs	Heatsink Volume= Hf x L x Whs	mm3	[redacted]
		cm3	[redacted]
s/L	Heatsink Air Channel width/Length ratio		[redacted]
km	Heatsink material thermal conductivity	W/m.K	[redacted]
kair,o	Air thermal conductivity	W/m.K	[redacted]
δ	Air density	Kg/m3	[redacted]
ν	Air viscosity	m2/s	[redacted]

Considering average pitch

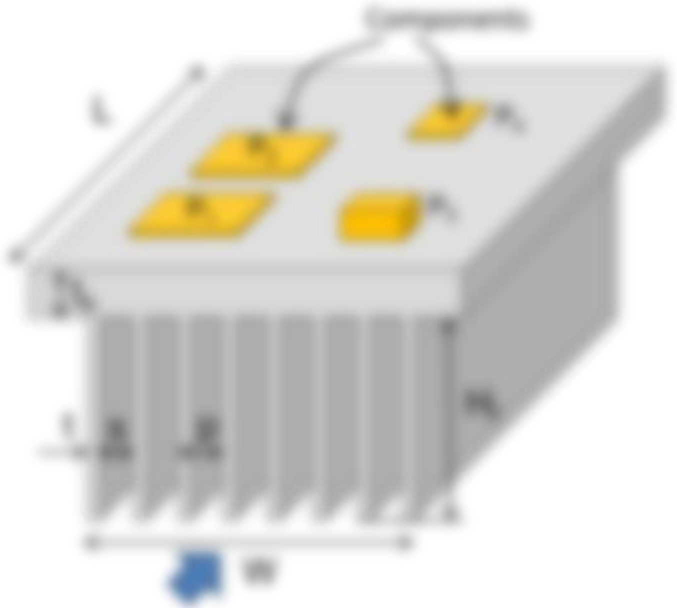
8.TDK DC-DC Converter: Heat sink thermal resistance （2）

h	Forced convection heat transfer coefficient	$W/m^2\cdot°C$	[redacted]
hnv	Natural convection Vertical heat transfer coeff	$W/m^2\cdot°C$	[redacted]
hnhb	Natural convection Horizontal heat transfer coeff	$W/m^2\cdot°C$	[redacted]
γ Hf			[redacted]
η f	Fin efficiency		[redacted]
Natural Convection			
Rth,fin	Heatsink Fin thermal resistance	°C/W	[redacted]
Rth,base,conv	Heatsink base convection thermal resistance	°C/W	[redacted]
Rth,hs	Heatsink thermal resistance	°C/W	[redacted]
Forced Convection			
Rth,fin	Heatsink Fin thermal resistance	°C/W	[redacted]
Rth,base,conv	Heatsink base convection thermal resistance	°C/W	[redacted]
Rth,hs	Heatsink thermal resistance	°C/W	[redacted]

Results of computed thermal resistance for the finned area of the heat sink.

9．Two-dimensional (2D) heat transfer analysis in the heat sink.

			[illegible]	[illegible]
H	Fin高さ	mm	20	20
t	Fin厚	mm	1.2	1.2
s	Fin-Fin間	mm	[illegible]	[illegible]
p	Finピッチ	mm	[illegible]	[illegible]
Nf	Number of Fins		16	16
W	Heatsink Fin area width	mm	[illegible]	[illegible]
L	Fin channel length (Avg)	mm	[illegible]	



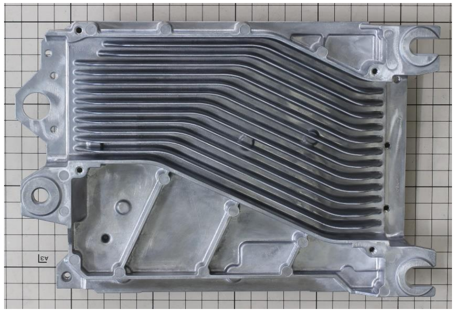
The traditional analysis of the heat removal by a heat sink assumes, (1) a single heat source or, (2) that the heat source occupies the entire area of the heat sink. The interaction (heat coupling) between the components is not taken into account. In this section, the temperature distribution (2D), originated by multiple heat sources, on the surface of the heat sink, is analyzed. The results are used to determine each device/component temperature and to extract the thermal circuit network.

Material Parameters

km	Thermal conductivity of heatsink metal	W/m.℃	210
heff	Finned heatsink Effective heat convection coefficient	W/m2.℃	180
hn	Unfinned Effective heat convection coefficient	W/m2.℃	10
tb	Thickness of Heatsink base plate	mm	10
Δx	Unit analysis cell size	mm	4
ζ	Fractional base thickness for lateral thermal conduct.		0.5
r	Heatsink base lateral thermal resistance		1
Rhc	Fiined Effective heatsink convection resistance		347
γ	r/Rh		0.0027
Rhn	Unfined Effective heatsink convection resistance		6250
η	r/Rhn		0.0002

				Thermal Conductivity k [W/m・℃]
1	Case, Heat sink	Heat sink	Aluminum	210
2	Insulating Thermally conductive sheet	Transistor-Heat sink	Furukawa Electric	5
3	TIM (Thermal Interface Material)	Diode-Heat sink		5
4	PCB Laminate	PCB	Mitsubishi Gas Chemical FR-4(EL190T, FL700)	0.4
5	Copper	PCB traces	Cu	380
6	Magnetic Core (Ferrite)	Transformer, Coil	TDKフェライト概要 TDK-EPCOS	5

TDK DC-DC Converter Thermal Performance: Simulation (1)



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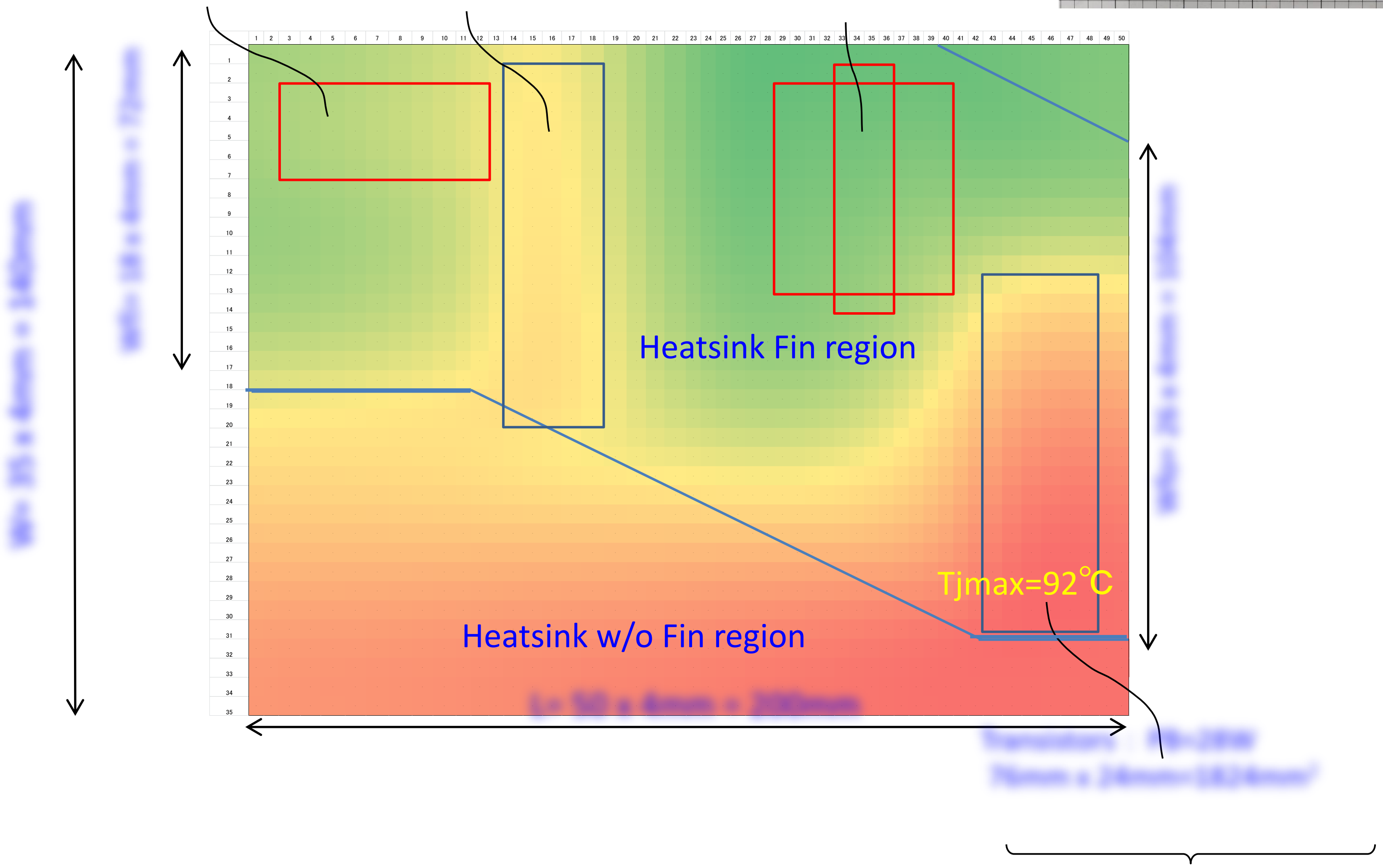

[redacted]

[redacted]

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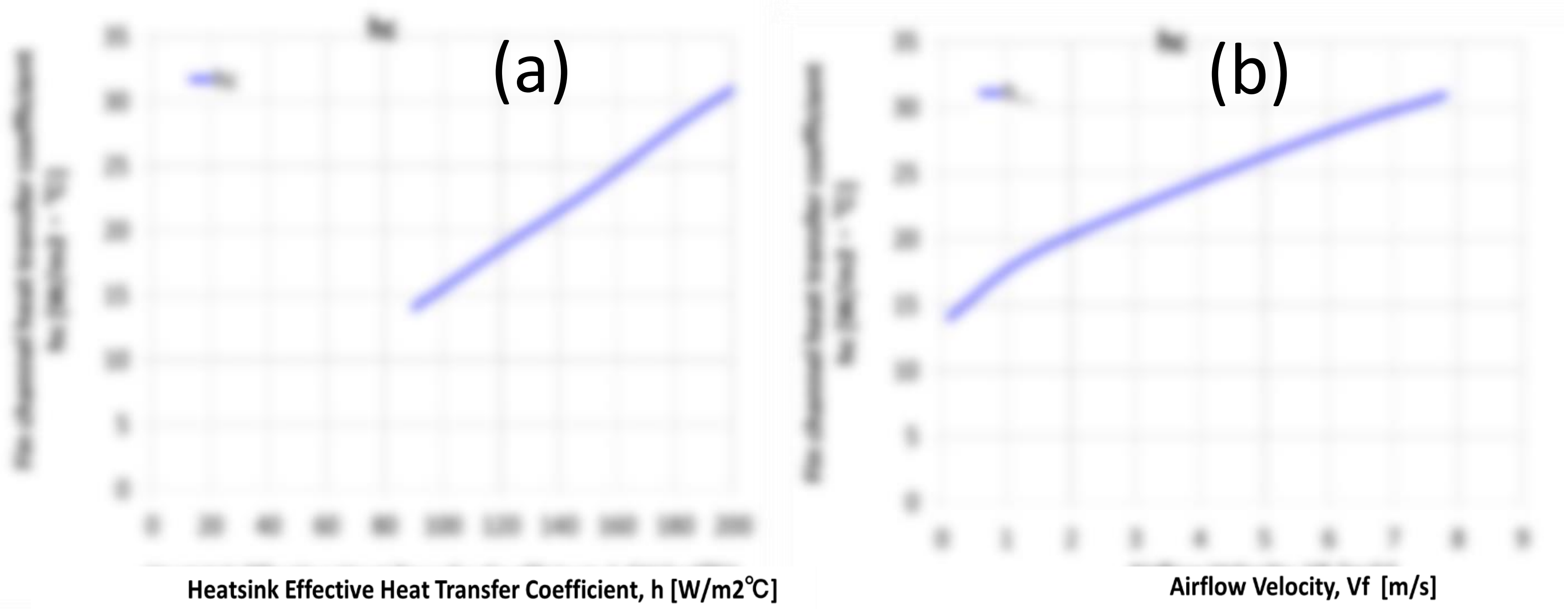
[redacted]

[redacted]

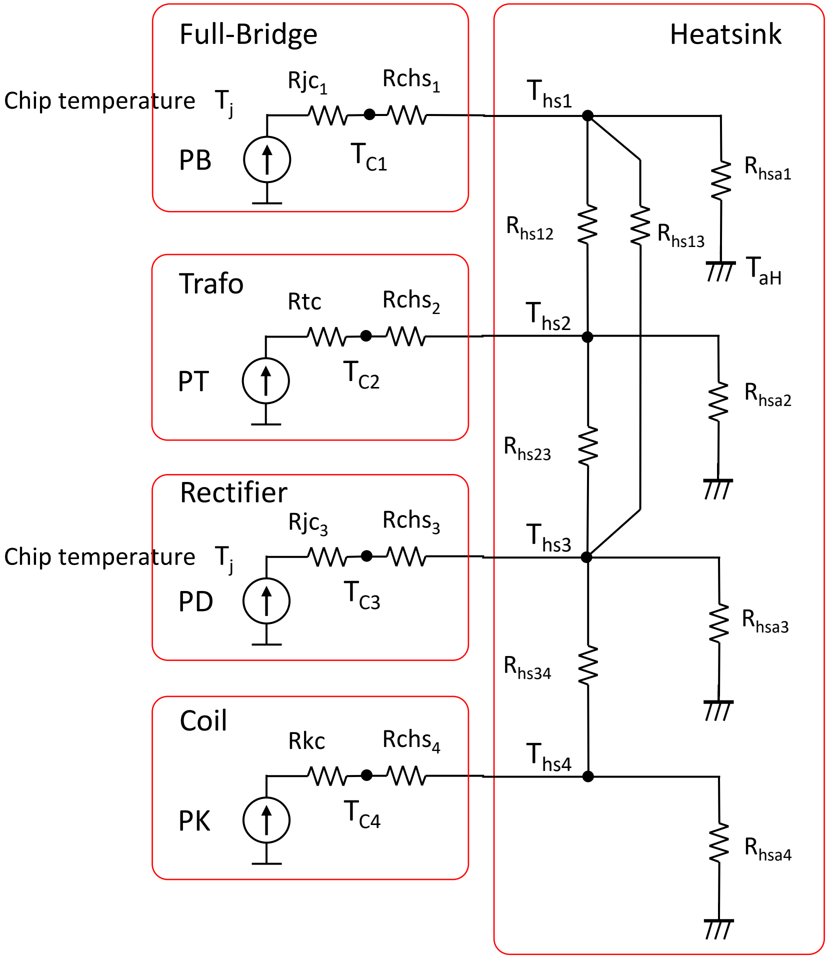
Heat sources temperatures for Ta=50°C and P1=P2=35W



a) Relationship between the heat sink effective heat transfer coefficient h_{eff} (x-axis) and the fin channel convection heat transfer coefficient hc.
b) The heat sink fin channel convection heat transfer coefficient hc versus the air flow speed (Vf).

From these results, for instance, to realize an effective h_{eff}=180W/m^2·°C (corresponding to a fin channel convection heat transfer coefficient hc~28W/m^2·°C) the air flow velocity of Vf~6m/s is required.

10. Equivalent Thermal circuit for the DC-DC converter (1)

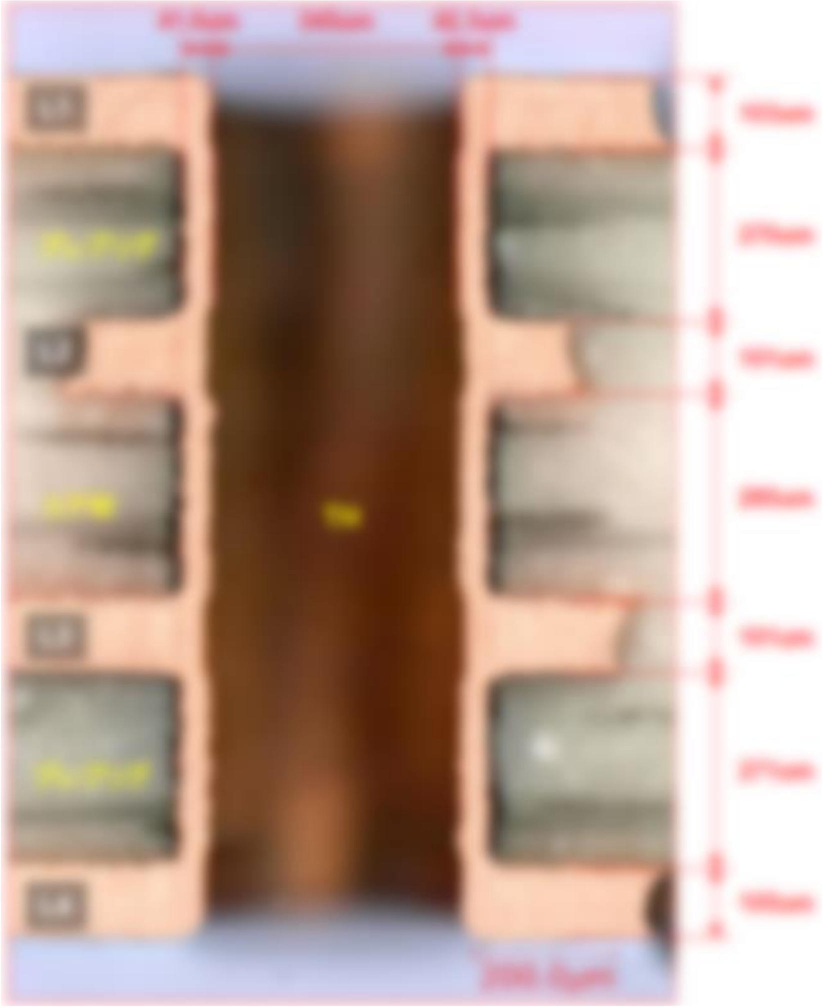


		[°C/W]
Rjc1	MOSFET Junction-pkg case	0.1
Rchs1	MOSFET pkg case-heatsink * Insulating conductive heat sheet	0.4
Rtc	Transformer-case	0.5
Rchs2	Transformer case-Heat sink	
Rjc3	Diode Junction-pkg case	0.11
Rchs3	Diode pkg case-heatsink * Effect of PCB Via is dominant	1
Rkc	Output Coil Core-Surface	3
Rchs4	Output Coil Surface-heatsink	2
Rhsa1	Full-Bridge Heatsink-Ambient air	2.3
Rhsa2	Transformer Heatsink-Ambient air	5
Rhsa3	Diode Heatsink-Ambient air	2.7
Rhsa4	Output Coil Heatsink-Ambient air	3
Rhs12	Thermal coupling Full-Bridge-Transformer	2
Rhs13	Thermal coupling Full-Bridge-Rectifier	4
Rhs23	Thermal coupling Transformer-Rectifier	2
Rhs34	Thermal coupling Rectifier-Coil	1.5
Tj	Semiconductor Junction temperature	
Tc	Device/Component Case temperature	
Ths	Heatsink Component side temperature	
TaH	Ambient (Heatsink Fin surface) temperature	50°C
PB	Full-Bridge power loss (k=4)	28W
PD	Rectifier Diode dissipation	64W
PT	Transformer power loss	12W
PK	Output Coil power loss	6W

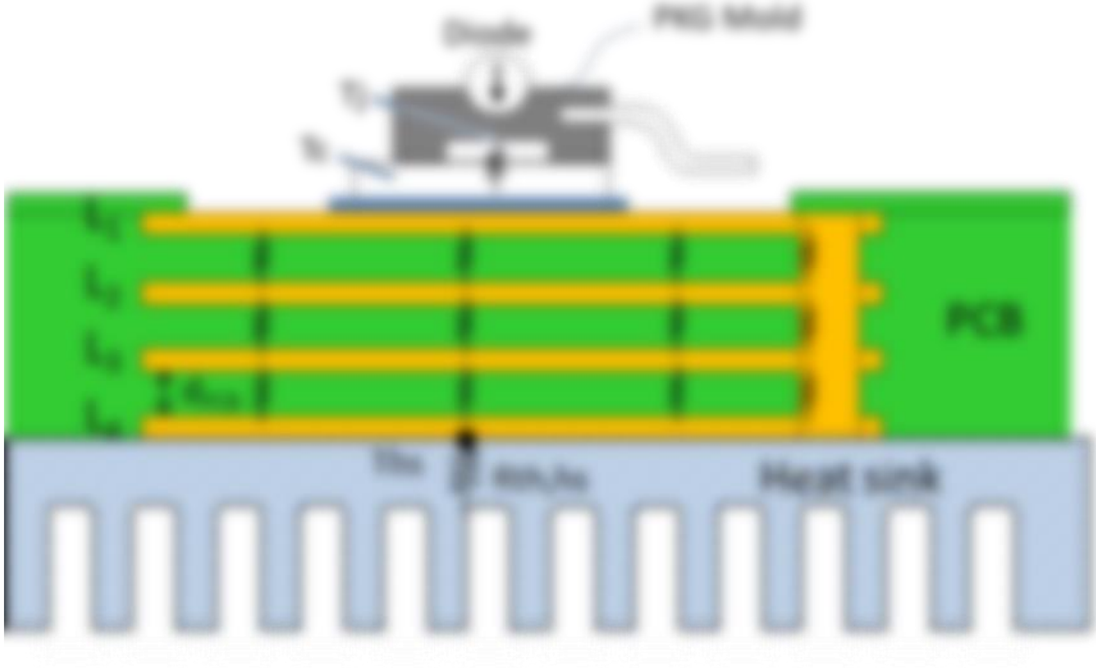
Extracted DC-DC converter equivalent thermal network (TM) including the main heat generation sources and effective thermal resistances.

11. Appendix

11.1 PCB via structure and the wiring thickness



11.2 PCB Cu pad (L1-L4) thermal resistance Rectifier diode (1)



A_{CuPad}=1220mm^2