 ISSN: 2321-8169
6110 - 6117

Heat Exchanger Developed for Inverter System using Copper

Triangular Corrugated Fin Technology

Pal Riya Bipradas Sanchita
ME , Dept.ETRX , Power Electronics , PIIT , Mumbai University
Navi-Mumbai , India
riyapal795@gmail.com

Abstract **—** Work performed and explained in this paper demonstrates: analysis of existing aluminum heat exchangers used in inverters (specifically: Sukam -900 whose operating temperature is limited to 40^0C), designing and manufacturing technology used for new heat exchanger which utilizes copper metal, installation and its thermal testing on inverter system .

Keywords - *Thermal conductivity (k),Corrugated fin technology, PTC-Cu Heat Sensor , Heat flux (q).*

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I. INTRODUCTION

Thermal management of inverter system is achieved by the use of only passive cooling mechanism where mainly aluminum (Al) metal is highly preferred over copper to form hardware cooling structures. Applying more number of mini-fans inside the inverter system not only increases the weight but also space consumption and slight hike in per inverter cost. There always exist a trade-off between performance, space, weight and cost. Aluminum heat sink even though it is light in weight, its performance towards heat transfer rate is quiet low (i.e 204W/m_K) when compared with copper material's heat conduction rate (i.e: 385W/m_K). Way to use copper material as heat sink / exchanger for inverter system with high performance of heat channeling, low weight and not too hike in per inverter's cost is demonstrated via this paper.

II. LITERATURE SURVEY

Work performed by Scot K. Waye, Jason Lustbader, Matthew Musselman, and Charles King , [1] , demonstrates an air-cooled inverter configuration using an optimized heat exchanger in an inverter consisting of an aluminum heat sink with equally spaced rectangular channels. Through a parametric computational fluid dynamics study, the heat sink was optimized for weight and volume by varying geometric parameters, including channel height, length, width, and device location. The test bench for this project used compressed air. The air passed through a plate heat exchanger for temperature control and entered the heat exchanger test section, shown in Figure 2. Ceramic resistance heaters (8 mm × 8 mm) provided the heat load; power was adjusted to yield the desired junction temperature for each flow rate.

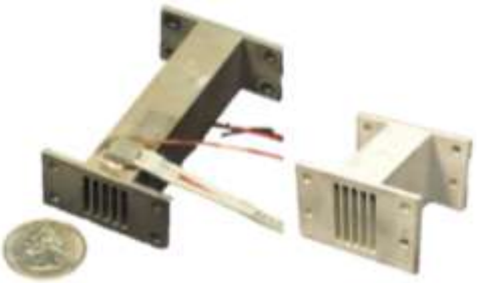

Fig. 1. Baseline (left) and optimized (right) sub-module heat exchangers fabricated from 6063 aluminum. Heaters are mounted on the top and bottom of the test section, one near the inlet edge and the other farther back. The flanges are for experimental convenience in attaching the test section to the inlet and outlet manifolds.

Fig. 2. Baseline aluminum sub-module test section. Ceramic resistance heaters providing the heat load are located on the top left and bottom right of the test section. Air flows from left to right.

Paper [2] proposed by Mark Gerber, Jan Abraham Ferreira, illustrates direct and indirect heat removal structures made using aluminum metal basically for high density inductors. Same can also be applied for transformer used in inverters by slightly modifying the design.

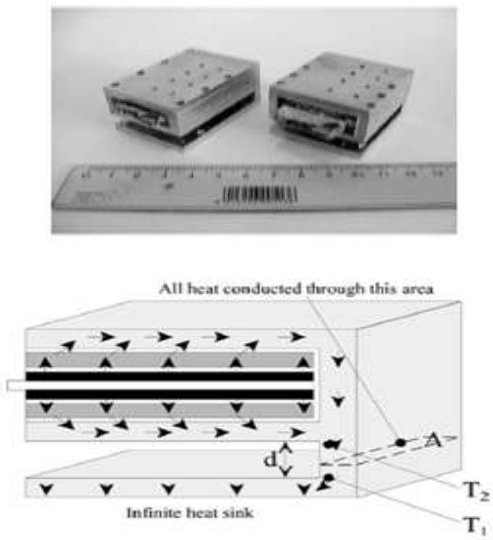

Fig 3 : ***Top*** :Photograph of the two structures. Left: indirect heat removal; right: direct heat removal. ***Bottom*** **: I**ndicates heat flow path.

Research study [3] conducted by Jeong Hyun Kim, Gyo Woo Lee on "Performance Evaluation of Extruded-Type Heat

Sinks Used in Inverter for Solar Power Generation", evaluates heat release performances of the three extruded-type heat sinks that can be used in inverter for solar power generation. Numbers of fins in the heat sinks (namely E-38, E-47 and E-76) were 38, 47 and 76, respectively. Heat transfer areas of them were 1.8, 1.9 and 2.8m^2. The heat release performances of E-38, E-47 and E-76 heat sinks were measured as 79.6, 81.6 and 83.2%, respectively. The results of heat release performance show that the larger amount of heat transfer area the higher heat release rate. While on the other, in this experiment, variations of mass flow rates caused by different cross sectional areas of the three heat sinks may not be the major parameter of the heat release.

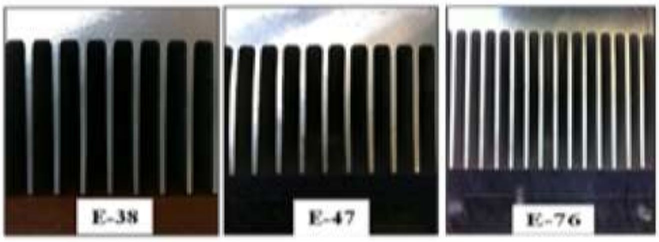

Fig 4: Extruded-type heat sinks (namely E-38, E-47 and E-76) with 38, 47 and 76, respectively.

III. HEAT SENSOR USED IN THIS EXPERIMENT

A. PTC-Cu SENSOR

A new PTC-Cu based temperature/heat sensor is shown in figure 6 below. It is possible to measure temperature/heat of above 1000^{0}C using this PTC-Cu sensor. PTC & Cu both of them are joined with cyanoacrylate ester.

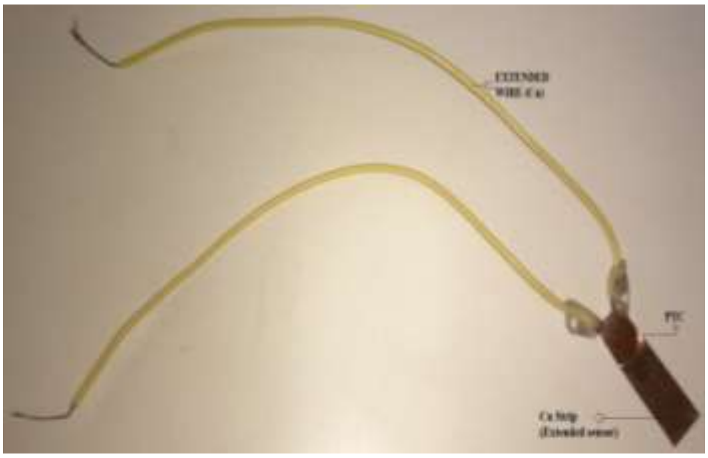
Fig 5: PTC-Cu Based Heat/Thermal Sensor

B. TESTING OF 'PTC-Cu SENSOR'

Since PTC has been used, the sensor's resistance will increase with increase in the temperature/heat being sensed. But practically, slight fluctuation in the resistance value will happen. Simple experiment was conducted where temperature of water was raised linearly using a heat source as shown in figure number 6.


Fig 6: Experimental Setup For Testing "PTC-Cu" Heat Sensor

C. DATA TABLE OBTAINED FROM THE ABOVE TEST

TABLE 1 : PTC-Cu DATA SHEET

TEMPERATURE 'T' (^{0}C)	**RESISTANCE 'R' (KΩ)**
40	4.70
41	4.90
42	4.92
43	4.95
44	5.1
45	5.3
46	5.6
47	5.7
48	5.9
49	6.3
50	6.4
51	6.9
52	7.3
53	7.4
54	7.5

Average of Temp (T) = 705/15 = 47^{0}C
Average of Resistance 'R' = 88.87/15 = 5.92KΩ
1 KΩ = 47/5.92= 7.93 = **8^{0}C** .... **(1)**

IV. THERMAL TEST PERFORMED ON INVERTER HAVING ALUMINUM HEAT SINK (CURRENTLY AVAILABLE IN THE MARKET)

A. TEST

PTC-Cu sensor was used to test inverter's (sukam 900 model) temperature which is presented in this paper. Basically in thermal management in both mechanical field and electronics field, run time temperature data/ information need to be obtained accurately as well as efficiently. Fluctuations noted in PTC-Cu based sensor is very negligible. Exact resistance value reading (at a specific temperature value) is indicated via multi-meter connected to the extended wires of this sensor. Ω value fluctuation seen on the multi-meter is very less. For inverter's temperature sensing , 4 PTC-Cu sensors were used to measure temperature of aluminum heat sinks located at 4 heat source locations within the inverter marked as L1 , L2 , L3 & L4 in below figure 7 below. Experiment was carried out for 60minutes. Resistance table was obtained shown in below TABLE 2. TABLE 3 is

ISSN: 2321-8169
6110 - 6117

derived based on the equation1. Experiment was conducted at room temperature 27^0C.

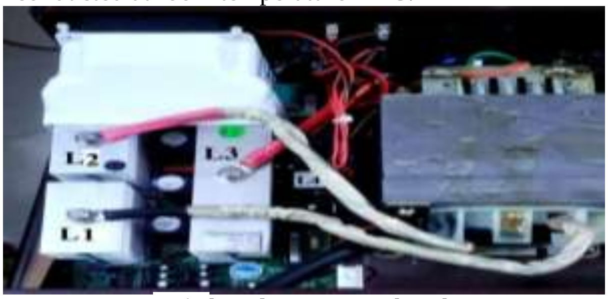

Fig 7: "Al" heat locations within the inverter.

Note :
C1 : components at location 1 (L1), C2 : components at location 1 (L2) , C3 : components at location 1 (L3), C4 : components at location 1 (L4) shown in fig 8 & 9 below.

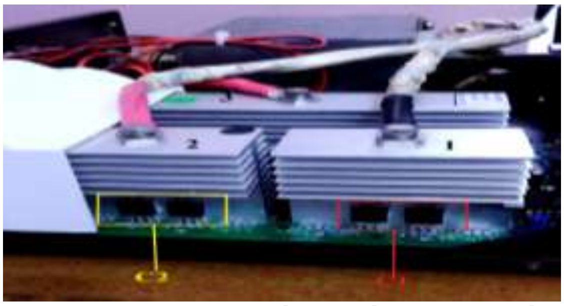
Fig 8 : Location 1 & 2 with C1 and C2 respectively.

Fig 9 : Location 3 & 4 with C3 & C4 respectively.

B. *ALUMINUM HEAT SINKS GEOMETRICAL SPECIFICATIONS*

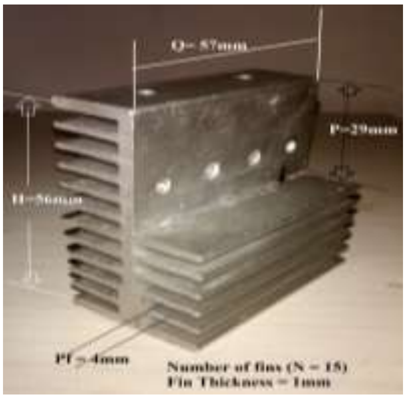
Fig 10: Existing aluminum heat sink/ exchanger at location L1 & L2 (identical).

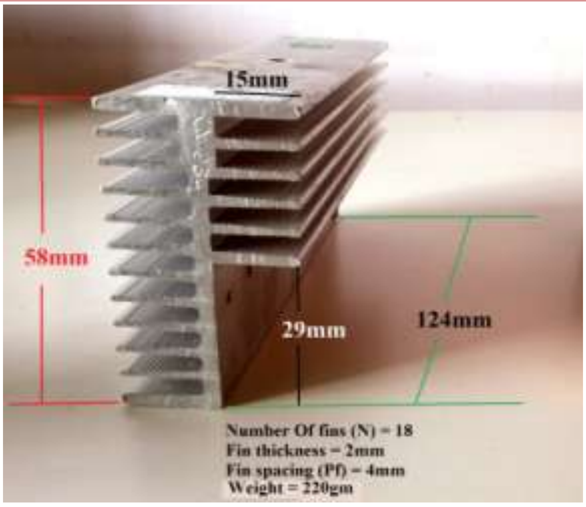

Fig 11: Existing aluminum heat exchanger at location L3.

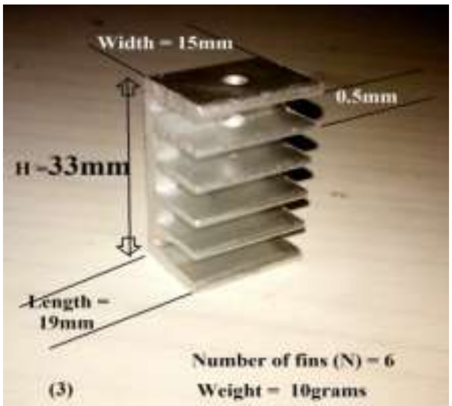

Fig 12: Existing aluminum heat exchanger at location L4.

C. *DATA OBTAINED*

TABLE 2 : RESISTANCE TABLE OF LOCATIONS L1-L4

Time (min)	Sensor 1 S1 in KΩ at L1	Sensor2 S2 in KΩ at L2	Sensor3 S3 in KΩ at L3	Sensor4 S4 in KΩ at L4
Initial 0	3.76	3.92	4.2	6.08
10	3.88	4.03	4.41	6.27
20	3.97	4.11	4.60	6.47
30	4.02	4.15	4.73	6.78
40	4.06	4.17	4.81	6.92
50	4.06	4.15	4.88	7.01
60	4.13	4.25	4.90	7.23

TABLE 3 : TEMPERATURE OF ALUMINUM HEAT SINK AT LOCATIONS L1-L4

Time (min)	Temp T1 in ^{0}C	Temp T2 in ^{0}C	Temp T3 in ^{0}C	Temp T4 in ^{0}C
Initial 0	30.08	31.36	33.60	48.64
10	31.04	32.24	35.28	50.16
20	31.76	32.88	36.80	51.28
30	32.16	33.20	37.84	54.24
40	32.48	33.36	38.48	55.36
50	32.48	33.2	39.04	56.08
60	33.04	34.00	39.20	57.84

TABLE 4: COMPONENTS (C1-C4) TEMPERATURE

Time (min)	**Temp of C1 in ^{0}C**	**Temp of C2 in ^{0}C**	**Temp of C3 in ^{0}C**	**Temp of C4 in ^{0}C**
Initial 0	27.50	28.50	29.00	30.00
10	28.50	29.00	30.00	32.00
20	27.50	28.00	30.00	33.00
30	28.50	29.00	31.00	33.00
40	28.50	29.50	31.00	34.00
50	28.50	29.50	31.50	34.50
60	29.00	30.00	32.50	35.00

D. CALCULATIONS

HEAT FLUX GERNERATED BY SINGLE COMPONENT

Power consumed by the inverter = 45 W where Load = 1 Fans (45W with rpm 400)
Area under C1 = 0.4cm^2
Heat flux (q) = $\frac{Q}{A}$ =Power utilized/Area= 45/0.9 = **112.5W/cm^2**

V. NEWLY DEVELOPED COPPER HEAT EXCHANGER

A. BASIC OF THE DESIGN :

[4] Aluminum heat sink at location L1 to L4 was replaced by newly designed copper heat sink. New cooling unit (shown in fig 13,C) which has been designed using copper, consist of 2 parts. First part is the "corrugated triangular fins" structure (fig 13,A) and the second part is the "base"(fig 13,B). Number of fins (N), height of fins (H), spacing between fins (Pf), fin thickness (Ft or (Ta= Tb1=Tb2)) and base plate thickness (b) , base plate length (w) & width (L) will vary from one application to other. The structure shown in (fig 13,C) is a long running structure. This complete structure can be folded into any geometrical shape such as one shown in cylindrical form (fig 14,D). Base plate acts as an extra supporting part which will provide mechanical support as well as it will improve thermal conduction. If number of fins are less then height is to be increases when heat flux value is high. Even for high heat flux if number of fins are more then height of fins should be kept low but spacing between fins must be taken care. It is to be noted that the 2 parts are made up of copper strip. It won't provide sufficient cooling performance if any one of the part (base or fins) is made up of either copper or aluminum [6].

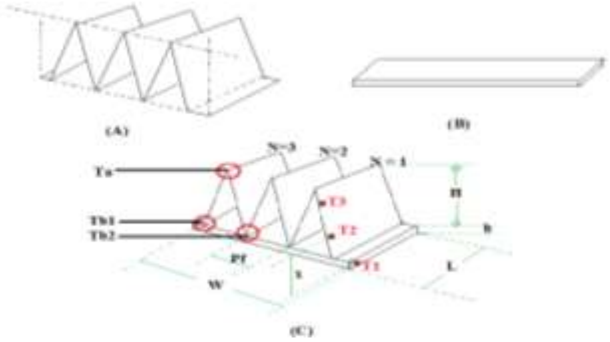

Fig 13: (A) The corrugated triangular fins structure . (B) Base plate. (C) Complete unit.

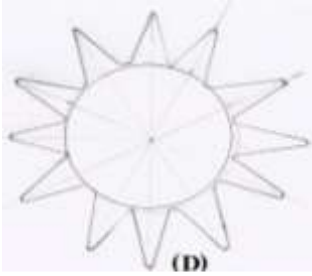

Fig 14: Circular /Cylindrical Structure.

From above fig (13,C), two conditions/cases are illustrated for heat transfer to take place to take place through corrugated structure. The T1,T2 &T3 represents highest temperature, mid temperature and low temperature respectively The flow of heat (Q) will always happen from higher temperature zone to lowest temperature zone in contact .

Thus
Q = f1(T1, T2, strip geometry, material) …….. (2)
The relation between T1 and T2 is in the form of temperature difference (T1-T2) and 'x' is the separation distance between T1 & T2.
Q = f2 (T1-T2, strip geometry, material) ……. (3)

Case 1:
If (T1-T2) = 0 (i.e.: when T1 = T2)
Then Q = 0 (means no heat/ thermal transfer rate is being taking place between points at T1 & T2

Case 2 :
If T1>T2
Then Q>0 (means heat transfer rate increases)
Q α (A * (T1-T2)/L)
Q = (k *A * (T1-T2)/L)
Q = - (k *A * (T2-T1)/L) (unit: watts)
Q_x = -K.A (dT/dx) …..… (4)

This is the heat transfer at x direction.
For y and z direction (in 3D representation), Q is given as:
Q_y = - K.A(dT/dy) ………. (5)
Q_z = - K.A (dT/dz) ……….. (6)

Note: for a very thin copper strip, heat conduction in 3D form can be neglected. Heat flow in any 1 direction can be considered for simplicity.

Heat Flux (q) is defined as the 'rate of flow of heat' and Critical heat flux is the 'thermal limit of a phenomenon where a phase change occurs during heating'.
q = Q/A

B. IMPORTANCE OF EVERY PARAMETER

[5] Thermal Conductivity **(K) = (Q*L)/(A*∆T)** …. (7)

1. Temperature difference (∆T) :
Greater the temperature difference between the two ends of the bar or the strip, greater will be the rate of heat flow.

Q α ΔT …. (8)

2. Cross-sectional area (A):

A bar twice as wide conducts twice the amount of heat.

Q α A …. (9)

3. Separation length/ distance (L) :

Rate of heat transfer is always inversely proportional to the length of the bar.

Q α (1/L) ….. (10)

4. Time (t):

Heat flow (Q) directly depends on the amount of time that passes. Twice the time, twice the heat.

C. TECHNOLOGY USED TO DEVELOP CORRUGATED TRIANGULAR FIN COPPER HEAT EXCHANGER/SINK

Technology which has been decided to be used : "corrugated fin technology". Where ever it is required to have high fin density on a restricted surface area at low weight and low manufacturing cost, corrugated fin technology is given much more importance compared to other technologies such as :

- Extruded
- Bonded
- Die-casting
- Skiving
- Machining
- Forging
- Stamping

Corrugated fins are manufactured by folding continuous strip of copper or aluminum in either a square wave , rect wave , u-wave or in a triangular wave patterns. After folded fins are manufactured, one can attach a base strip which helps increasing the heat transfer surface area. Below fig 15 represents the machine used to form triangular corrugated fin structure.

Fig 15: ***Top***: Complete View Of The Manually Controlled Corrugated Machine. ***Bottom*** : Triangular Press Region Of The Machine.

D. DEVELOPED COPPER HEAT SINK SPECIFICATIONS

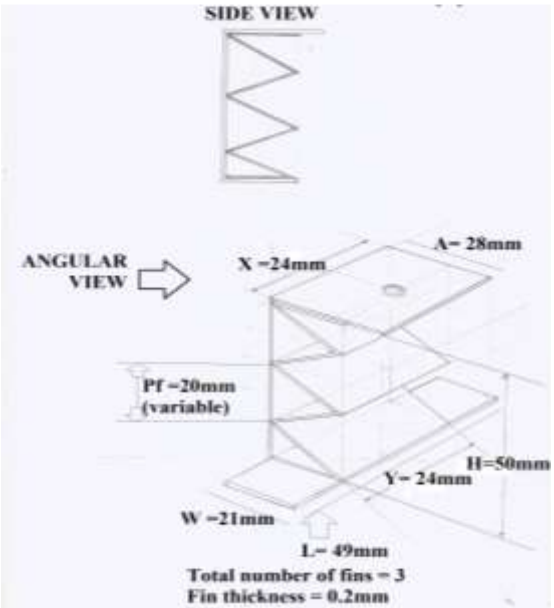

Fig 16 : Copper heat sink/exchanger developed for location L1 & L2 (identical).

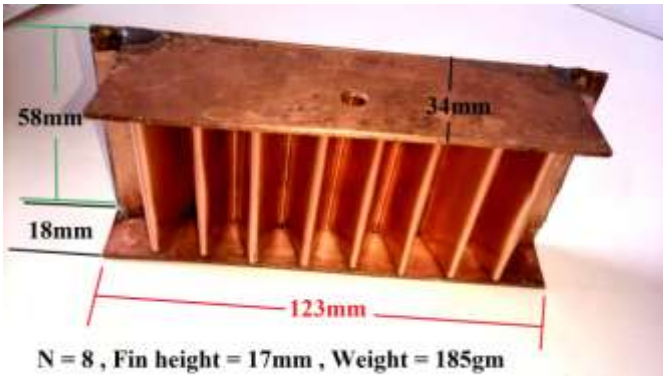

Fig 17 : Copper heat sink/exchanger developed for location L3.

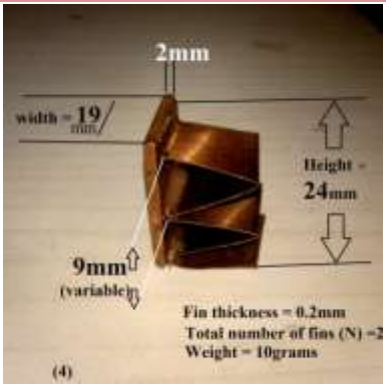

Fig 18 : Copper heat sink/exchanger developed for location L4.

E. DATA OBTAINED

Thermal test on inverter system with newly developed copper heat sink/ heat exchanger was carried out in the same way as done with aluminum heat sink (explained above). Data obtained in this test is depicted in TABLE 5 -7. Table 6 is obtained using equation 1.

TABLE 5 : RESISTANCE TABLE OF LOCATIONS L1-L4

Time (min)	**Sensor 1 S1 in KΩ at L1**	**Sensor2 S2 in KΩ at L2**	**Sensor3 S3 in KΩ at L3**	**Sensor4 S4 in KΩ at L4**
Initial 0	4.06	4.20	4.56	5.50
10	4.63	4.62	4.71	7.35
20	4.74	4.71	4.86	7.13
30	4.90	4.80	5.00	7.80
40	4.90	4.80	5.00	7.70
50	4.86	4.74	5.08	7.33
60	5.00	4.90	5.10	7.90

TABLE 6 : TEMPERATURE OF COPPER HEAT SINK AT LOCATIONS L1-L4

Time (min)	**Temp T1 in ^{0}C**	**Temp T2 in ^{0}C**	**Temp T3 in ^{0}C**	**Temp T4 in ^{0}C**
Initial 0	32.48	33.60	36.48	44.00
10	37.04	36.96	37.68	58.80
20	37.92	37.68	38.88	57.04
30	39.20	38.40	40.00	62.40
40	39.20	38.40	40.00	61.60
50	38.88	37.92	40.64	58.64
60	38.88	39.20	40.80	63.20

TABLE 7: COMPONENTS (C1-C4) TEMPERATURE

Time (min)	**Temp of C1 in ^{0}C**	**Temp of C2 in ^{0}C**	**Temp of C3 in ^{0}C**	**Temp of C4 in ^{0}C**
Initial 0	27.00	27.00	27.70	31.00
10	27.00	27.00	28.00	30.00
20	28.00	27.50	28.00	33.00
30	28.50	27.50	28.00	32.00
40	28.00	28.00	28.50	32.00
50	28.00	28.00	29.00	33.00
60	27.50	28.00	29.00	33.00

F. COMPARISON

Every detail obtained during the test with aluminum heat sink was compared with data obtained using corrugated copper heat sink/exchanger. It was observed that copper heat sink's temperature was higher than aluminum heat sink and C1, C2, C3 & C4 components temperature was observed to be lower than what was observed during aluminum heat sink's case. This proved that since copper heat sink was consuming heat from the component rapidly, its temperature raised keeping the main component's temperature at low level. This is well depicted in below graphical plot fig 19- fig 22.

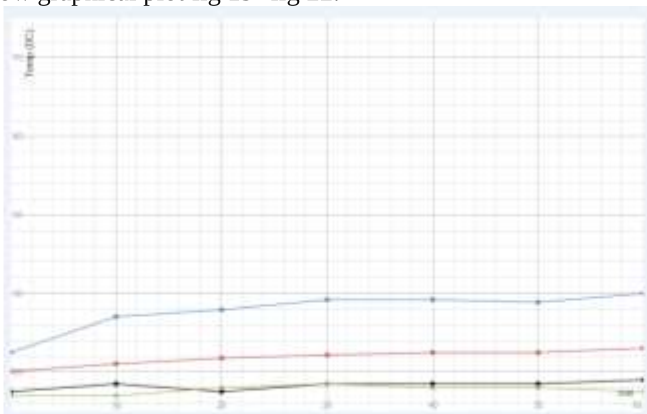

Fig 19 : **At Location 1 : (**Red: Al Heat Sink ,Blue : Cu Heat Sink, Black : Al Component , Green : Cu Component)

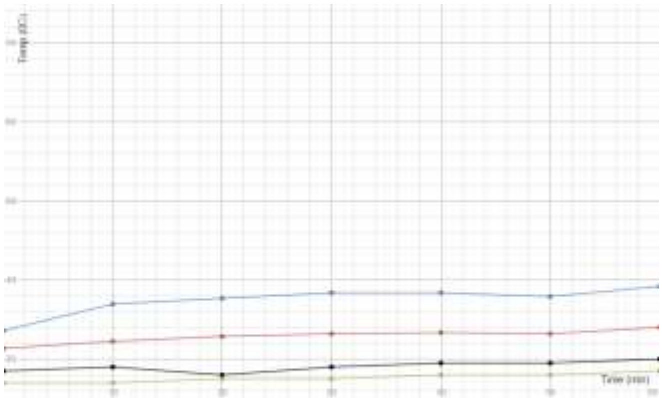

Fig 20 : **At Location 2 : (**Red: Al Heat Sink ,Blue : Cu Heat Sink, Black : Al Component , Green : Cu Component)

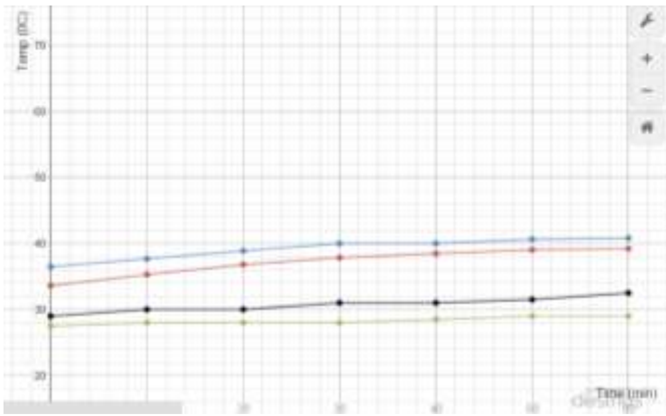

Fig 21 : **At Location 3 : (**Red: Al Heat Sink ,Blue : Cu Heat Sink, Black : Al Component , Green : Cu Component)

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6110 - 6117

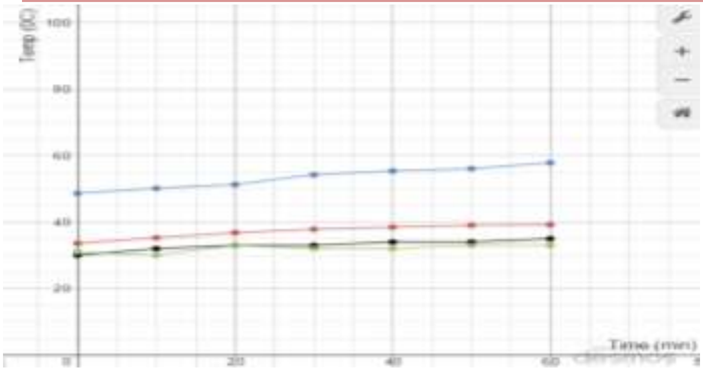

Fig 22 : **At Location 4 : (**Red: Al Heat Sink ,Blue : Cu Heat Sink, Black : Al Component , Green : Cu Component)

G. VARIOUS VIEWS OF THE COMPLETE INVERTER PCB WITH COPPER HEAT EXCHANGER

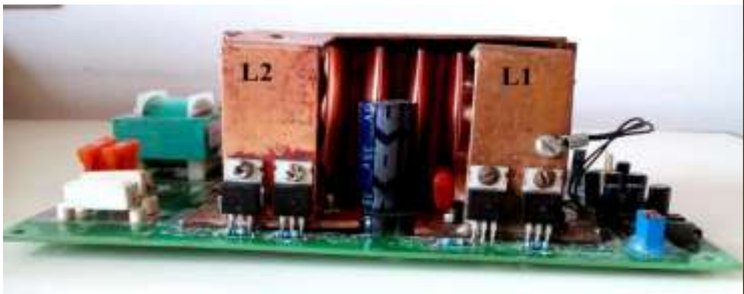

Fig 23: Front View

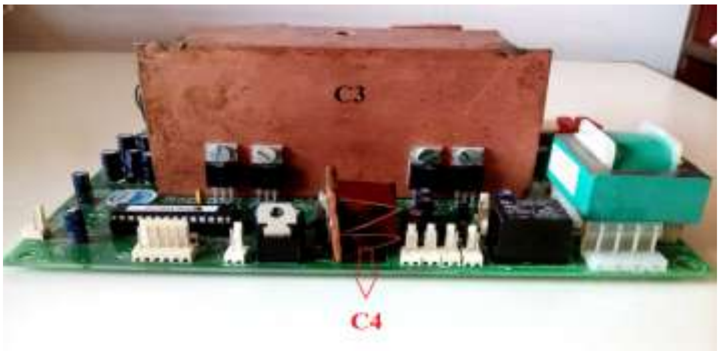

Fig 24: Back View

Fig 25: Top View

Fig 26 : Complete view showing "*PTC-Cu & Cu Heat Exchanger*" attached to the inverter's PCB board.

VI. CONCLUSION

Work performed and explained in this paper demonstrated: analysis of existing aluminum heat exchangers used in inverter (Sukam 900), designing and manufacturing technology used for new heat exchanger which utilizes copper metal strip, installation and its thermal testing on inverter system. Graphs plotted from fig 19-22 well illustrates that components reached low temperature level when copper heat exchanger was used to provide cooling mechanism to the inverter system when compared with aluminum heat exchanger. Comparing red and blue plotting , one can easily note that heat transfer path (from component to the heat exchanger) provided by copper heat exchanger was high. Test recorded proved that this designed copper heat exchanger using corrugated rect. fin technology provided a better hardware solution for thermal management of inverter 'Sukam 900 model'.

REFERENCES

[1] Scot K. Waye, Jason Lustbader, Matthew Musselman, and Charles King, "Air-Cooled Heat Exchanger for High-Temperature Power Electronics" , National Renewable Energy Laboratory, 2014 *IEEE Compound Semiconductor IC Symposium* San Diego, California October 19–22, 2014.

[2] Mark Gerber, Jan Abraham Ferreira, *Senior Member, IEEE*, Ivan W. Hofsajer, Member, IEEE, and Norbert Seliger ," A

High-density Heat-Sink-Mounted Inductor for Automotive Applications", *IEEE Transactions On Industry Applications*, vol. 40, no. 4, july/august 2004, PP 1031-1038.

[3] Jeong Hyun Kim, Gyo Woo Lee **, "**Performance Evaluation of Extruded-Type Heat Sinks Used in Inverter for Solar Power Generation", *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* Vol:7, No:12, 2013, PP 1407-1410.

[4] Mukesh Kumar , Anil Kumar , Sandeep Kumar,"Optimum Design And Selection Of Heat Sink",*International Journal of Application or Innovation in Engineering & Management* , Volume 2, Issue 3, PP 541-549, March 2013.

[5] *S.* Lee, "Optimum Design and Selection of Heat Sinks," Proceedings of 1 lth *IEEE Semi-Therm Symposium*, pp. 48-54, 1995.

[6] Ahmed Zaghol, Kem Hermann & James Butler, "Forced Convection Heat Transfer for swaged Mixed Metal Heat Sink", Micro-Electronics Heat Transfer Laboratory, Canada, PP 315-322.

AUTHOR

Er. PAL RIYA BIPRADAS SANCHITA received Bachelor Of Engineering in Electronics from PIIT (Pillai Institute Of Information Technology, Engineering, Media Studies & Research) under Mumbai University. Currently pursuing Master of Engineering. Her research areas are Power Electronics and Optical Communication. She is the author of (1) 'Free Space Light Communication'. (2) 'Negative Role of Atmosphere On Free Space Light Communication'. (3) 'Heat in Electronic Circuits and Material Selection Criteria for Cooling Solutions', (4) 'Measure Of Heat Conduction Through Copper', (5) HY510 Grease: Maximum Temperature Support And Its Application In Cob Led Heat Management , (6) PTC-Cu Heat Sensor & Its Application In Inverter's Thermal Testing , (7) Corrugated Technology based Copper Heat Exchanger for Efficient Thermal Management of Inverter System & (8) Thermal Management Of High Heat Dissipating Electronic Components: Led Module And Metal Diodes .