International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:14, No:12, 2020

Electronics Thermal Management Driven Design of an IP65-Rated Motor Inverter

Sachin Kamble, Raghothama Anekal, Shivakumar Bhavi

Abstract**—**Thermal management of electronic components packaged inside an IP65 rated enclosure is of prime importance in industrial applications. Electrical enclosure protects the multiple board configurations such as inverter, power, controller board components, busbars, and various power dissipating components from harsh environments. Industrial environments often experience relatively warm ambient conditions, and the electronic components housed in the enclosure dissipate heat, due to which the enclosures and the components require thermal management as well as reduction of internal ambient temperatures. Design of Experiments based thermal simulation approach with MOSFET arrangement, Heat sink design, Enclosure Volume, Copper and Aluminum Spreader, Power density, and Printed Circuit Board (PCB) type were considered to optimize air temperature inside the IP65 enclosure to ensure conducive operating temperature for controller board and electronic components through the different modes of heat transfer viz. conduction, natural convection and radiation using Ansys ICEPAK. MOSFET's with the parallel arrangement, IP65 enclosure molded heat sink with rectangular fins on both enclosures, specific enclosure volume to satisfy the power density, Copper spreader to conduct heat to the enclosure, optimized power density value and selecting Aluminum clad PCB which improves the heat transfer were the contributors towards achieving a conducive operating temperature inside the IP-65 rated Motor Inverter enclosure. A reduction of 52 ℃ was achieved in internal ambient temperature inside the IP65 enclosure between baseline and final design parameters, which met the operative temperature requirements of the electronic components inside the IP-65 rated Motor Inverter.

Keywords**—**Ansys ICEPAK, Aluminum Clad PCB, IP 65 enclosure, motor inverter, thermal simulation.

I. Introduction

INGRESS protection rating or International Protection rating, generally referred as IP rating is a standard to qualify electrical enclosures which are subjected to harsh environments and its effectiveness of providing sealing towards intrusion of dust and water. An IP65 rated enclosure provides total protection against ingress of solid foreign objects such as debris, sand, dust and limited ingress protection from multi-directional low-pressure water and oil jets that can damage the electronic components and circuits inside the enclosure [1].

An electrical motor inverter is used to control the speed or torque of the electrical motor as per design specifications which contribute towards improving productivity and efficiency of the electric motor [2]. Analysis of electronic components for thermal performance and corresponding effective thermal management plays a crucial role in the thermal life of electronic components in the area of power electronics which are subjected to harsh operating environments [3].

The purpose of this study was to design an IP65 rated electrical enclosure for the motor inverter by establishing an effective thermal management for the enclosure along with component arrangement, heat sink design, PCB type and establishing an effective heat transfer path through spreaders, thereby to optimize the air temperature inside the IP65 rated motor inverter enclosure to ensure a conducive operating temperature for inverter board, power board, controller board and various electronic components of the motor inverter.

Power electronic systems, like the motor inverter, which are designed for higher levels of heat flux, end up failing in thermal performance due to localized hot-spots due to arrangement of components such as MOSFET's. This localized hot-spot becomes a challenge, which has to be transferred using various combinations of heat spreaders and dissipated to the ambient by conducting it to the enclosure.

II. Numerical Modeling and Simulation

In the current work, 3D thermal simulation on an electrical motor inverter with its enclosure designed to meet the IP65 rating criteria was carried out to understand its thermal performance in terms of temperature of electronic components, touch temperature of enclosure and internal ambient temperature using commercial FVM code Ansys ICEPAK and Ansys Fluent solver.

A. Governing Equations

Navier Stokes Equation describes the three-dimensional motion of viscous fluids and consists of time-dependent continuity and momentum equation as in (1) and (2), respectively for an incompressible fluid flow and time-dependent energy equations as in (3) for solving the temperatures due to pre-dominant conjugate heat transfer phenomenon under consideration for electrical motor inverter,

$$\frac{\partial \rho}{\partial t} = -\rho\nabla . u \tag{1}$$

$$\frac{\partial u}{\partial t} = (u . \nabla)u - \frac{1}{\rho}\nabla P + \frac{F}{\rho} + \vartheta\nabla^2 u \tag{2}$$

$$\frac{\partial s}{\partial t} = -u . \nabla s + \frac{Q}{T} \tag{3}$$

The flow and energy equations (1)-(3) were solved for the defined boundary conditions to predict the thermal

Sachin Kamble, Raghothama Anekal, and Shivakumar Bhavi are with the HCL Technologies, Bengaluru, Karnataka, India (e-mail: sachin.kamble@hcl.com, raghothama.anekal@hcl.com, shivakumar.bb@hcl.com).

performance of the electrical motor inverter till convergence of continuity and momentum equations was to the order of $1e^{-4}$ and energy equations was to the order of $1e^{-10}$ along with the temperatures stabilizing across the system using Ansys Fluent solver.

B. Dimensionless Numbers for Natural Convection [4]

Grashof number (Gr) for natural convection is analogous to Reynolds number (Re) for fluid flow,

$$Gr = \frac{\rho^2 \beta g \Delta T L^3}{\mu^2} \quad (4)$$

Rayleigh number (Ra),

$$Ra = Gr * \mathrm{Pr} \quad (5)$$

Prandtl number (Pr),

$$Pr = \frac{\mu\, C_p}{k} \quad (6)$$

Dimensionless numbers for natural convection problems, Grashof number (Gr) characterizing the type of flow, being laminar or turbulent, Rayleigh number (Ra) characterizing the convection flow and Prandtl number (Pr) characterizing the diffusivity of flow in heat transfer problems were calculated using the FVM code in Ansys ICEPAK.

C. Fin Design [5], [6]

Area of fin surface is calculated using,

$$A = N * A_f + A_b \quad (7)$$

where A = Total surface area of fin, N = Number of fins, A_f = Surface area of each fin, A_b = Area of exposed base.

Using (7), the initial design of rectangular fins for the electrical motor inverter enclosure was calculated.

D. Electrical Motor Inverter and Operating Environment

The electrical motor inverter shown in Fig. 1 consisted of three PCBs namely inverter board, power board and controller board stacked one above the other and held with Aluminum standoffs and was designed with various electronic components according to desired functionality.

MOSFETs being the major contributor of the total power dissipation of the system, their arrangement to overcome localized hot-spots and conducting this heat to the enclosure for dissipating it to the environment was a challenge, which was contributing towards increasing the internal ambient temperature.

Due to high power density and multiple stacked PCBs, the major challenge envisioned was a higher internal ambient temperature which would hamper a conducive work environment for the components, restricting it to operate within the allowable operating temperature limits, while the motor inverter is being exposed to harsh external ambient conditions.

The inverter, power and controller PCBs were enclosed in an electrically insulated aluminum enclosure meeting the IP65 rating standards. This enclosure was a means of heat transfer path to conduct heat from the components and PCBs to dissipate it to the environment to meet the operative temperature requirements of electronic components, enclosure touch temperature and conducive internal ambient temperature.

The electrical motor inverter was required to be operating in a harsh ambient condition without any assistance of active cooling systems. So, natural convection was the mode of heat transfer from enclosure to the environment.

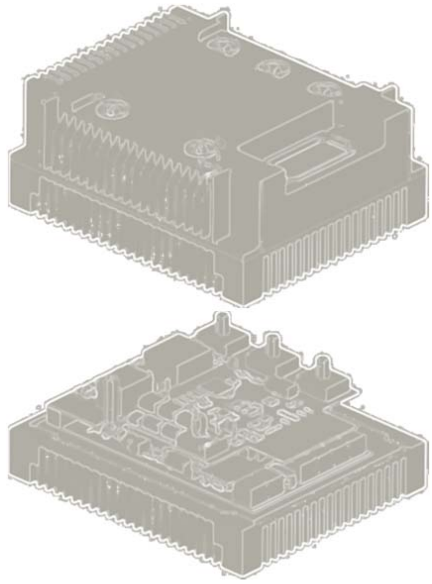

Fig. 1 Electrical motor inverter

E. Computational Natural Convection Domain and Boundary Conditions

Numerical investigation on four configurations of electrical motor inverter designs were carried out as per Tables I-IV, at an external ambient temperature of 50 °C based on design of experiments approach [7], [8].

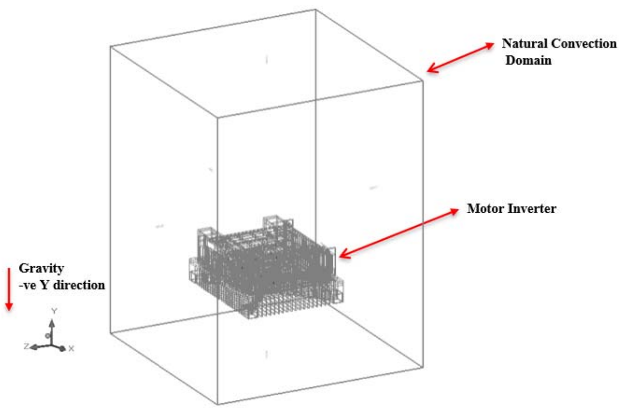

Fig. 2 Natural convection computational domain

To depict the electrical motor inverter operating in an environment with natural convection mode of heat transfer, a computational domain of 1.5 times the maximum dimension of the enclosure was created in the direction of natural convection plumes i.e. against the gravity direction and for all other directions, the computational domain was set-up as 0.5 times the maximum dimension of the enclosure as shown in Fig 2, which effectively captures the physics without being computationally expensive.

TABLE I
ELECTRICAL MOTOR INVERTER CONFIGURATION I

Configuration	Description
MOSFET arrangement	Staggered positioning on heatsink
Heat Sink Design	Top enclosure with rectangular fins and bottom enclosure with aluminum spreader
Heat Spreader	Aluminum Spreader
PCB Type	FR4
Enclosure volume (mm^3)	$9.5e^6$
Power Dissipation (W)	220

TABLE II
ELECTRICAL MOTOR INVERTER CONFIGURATION II

Configuration	Description
MOSFET arrangement	Staggered positioning on heatsink
Heat Sink Design	Top and Bottom enclosure with rectangular fins
Heat Spreader	Copper Spreader
PCB Type	FR4
Enclosure volume (mm^3)	$9.5e^6$
Power Dissipation (W)	220

TABLE III
ELECTRICAL MOTOR INVERTER CONFIGURATION III

Configuration	Description
MOSFET arrangement	Parallel positioning on heatsink
Heat Sink Design	Top and Bottom enclosure with rectangular fins
Heat Spreader	Copper Spreader
PCB Type	Aluminum Clad
Enclosure volume (mm^3)	$7.5e^6$
Power Dissipation (W)	80

TABLE IV
ELECTRICAL MOTOR INVERTER CONFIGURATION IV

Configuration	Description
MOSFET arrangement	Parallel positioning on heatsink
Heat Sink Design	Top enclosure without fins bottom enclosure with rectangular fins
Heat Spreader	Copper Spreader
PCB Type	Aluminum Clad
Enclosure volume (mm^3)	$7.5e^6$
Power Dissipation (W)	80

MOSFETs being the major heat dissipating component, 2R (two-resistance) model of the MOSFETs were created by defining the junction to case resistance R_{jc} (°C/W) and junction to board resistance R_{jb} (°C/W) values as per the manufacturer datasheet. Very less and uninfluencing heat dissipating components were thermally modeled by defining as a bulk model with thermal conductivity of 10 W/m-K to account for behavior of convection currents inside the enclosure.

Aluminum material properties were defined for the top and bottom enclosure heatsinks with rectangular fins and for the stand-off's connecting the three PCB's together. Thermal properties of air at 50 ℃ were defined in the domain. Radiation mode of heat transfer was considered with 0.8 emissivity for the black painted enclosure surface.

The natural convection domain and electrical motor inverter assembly were discretized using multi-blocks to create conformal hexahedral elements and established a conduction heat transfer path between the components and enclosures using Ansys ICEPAK counting to ~10 million elements.

High mesh density was maintained inside and on the electrical motor inverter to effectively capture the rectangular fins, free fluid between the fins and foot prints of the components and was coarsened away from the motor inverter towards the outer walls of the natural convection domain. The computational mesh of the enclosure is shown in Fig. 3.

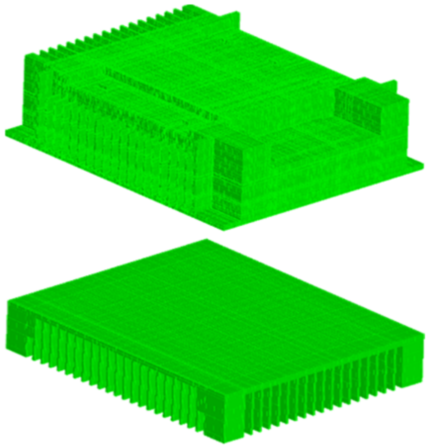

Fig. 3 Discretization of electrical motor inverter top and bottom enclosure

Steady state numerical simulations were performed at an external ambient temperature of 50 ℃. Reynolds Averaged Navier–Stokes Equation (RANS) equation was solved using Ansys Fluent FVM code in association with zero equation turbulence model due to natural convection flow domain around the electrical motor inverter. Gravity was defined in the "-ve" Y direction, being the opposite of convection plumes flow direction.

III. RESULTS AND DISCUSSIONS

The outcomes of the steady state 3D thermal simulation performed on the different design configurations of electrical motor inverter exchanging heat with the environment at 50 ℃ by means of natural convection are as follows:

1) The simulation results were studied primarily to understand the variation of internal ambient temperature inside the enclosure, which was an important factor for qualifying the system which allows for a conducive environment for the components to operate within the allowable operating limits.
2) Minimal difference in the internal ambient temperature values was observed in the heatsink design configurations

with top and bottom fin compared to top spreader and bottom fin configuration as in Fig. 5, due to the reason of MOSFETs mounted on the bottom enclosure which had rectangular fins and was a major contributor for heat transfer compared to the top enclosure with fins which did not significantly improve the heat transfer.

3) Touch temperature of the enclosure and the MOSFET temperatures were the other factors monitored to ensure the components were within the allowable operating temperature limits.
4) Area averaged value of touch temperatures on the top and bottom enclosures as captured in temperature contour shown in Fig. 4 was predicted to be 71 °C for configuration III as in Table III, being within the allowable limits.

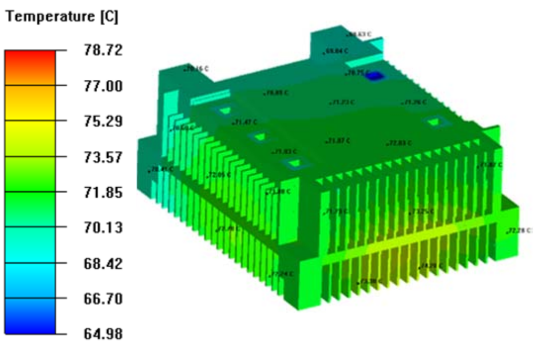

Fig. 4 Touch temperature distribution on the enclosure

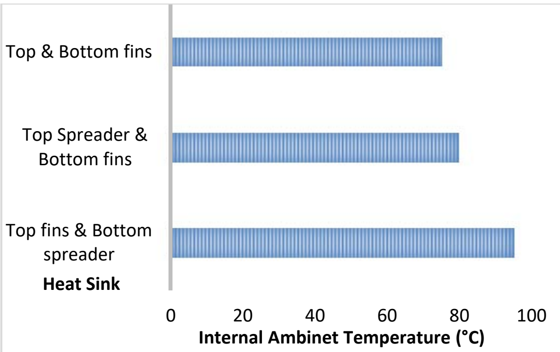

Fig. 5 Variation of internal ambient temperature with heat sink configurations

5) Variation of internal ambient temperature for different configurations as given in Tables I-IV is plotted in Fig. 6. Configuration I as in Table I, being the baseline had the highest area averaged internal ambient temperature of 131 °C and configuration III as in Table III predicted 79 °C.
6) Area averaged internal ambient temperature of 79 °C inside the enclosure as shown in the temperature contour in Fig. 7 was achieved with the design configuration III given in Table III and was conducive to enable the components and MOSFETs to operate within the allowable operating temperature limits, thereby reducing the internal ambient temperature inside the IP65 enclosure by 52 °C compared to baseline design configuration I given in Table I.

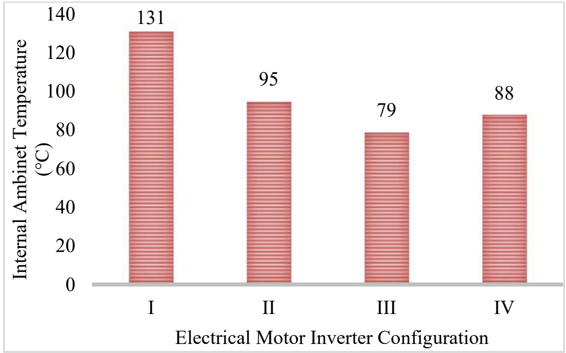

Fig. 6 Variation of internal ambient temperature with electrical motor inverter configurations

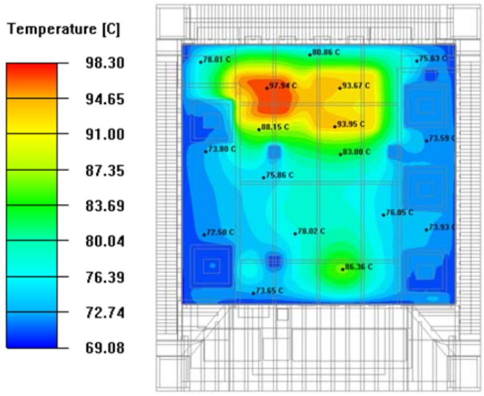

Fig. 7 Internal ambient temperature distribution inside enclosure

IV. Conclusion

In this work, numerical investigation on an electrical motor inverter was performed at 50 °C with conduction, natural convention and radiation mode of heat transfer for different design configurations incorporating zero equation turbulence model with 2R modeling approach for the MOSFET's.

Design configurations with different MOSFET arrangements, heatsink design, heat spreaders, PCB type and total power dissipations were studied. Based on the encouraging outcome of internal ambient temperature and enclosure touch temperature, configuration III designed with parallelly arranged MOSFETs, rectangular finned molded heat sink on both enclosures meeting the IP 65 rating standards, enclosure volume to satisfy the total power dissipation, copper spreader to conduct heat to the enclosure and optimized power density value were the qualified design which contributed towards achieving a conducive internal ambient temperature inside the IP-65 rated electrical motor inverter enclosure.

Baseline model (configuration I) had the highest internal ambient temperature of 131 °C and design configuration III predicted 79 °C. With this, it was achieved an area average reduction of 52 °C in internal ambient temperature inside the IP65 enclosure between baseline (configuration I) and final design parameters (configuration III) which met the allowable operative temperature requirements of the electronic components inside the IP-65 rated electrical motor inverter.

NOMENCLATURE

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCB	Printed Circuit Board
SMD	Surface Mounted Devices
FVM	Finite Volume Method
Gr	Grashof number
Ra	Rayleigh number
Pr	Prandtl number
ρ	Density (kg/m^3)
g	Gravity (m/s^2)
T	Temperature (°C)
L	Characteristic length (m)
μ	Viscosity (Ns/m^2)
C_p	Specific heat (kJ/kg K)
K	Thermal Conductivity (W/m-K)
t	Time (s)
s	Entropy
P	Pressure
F	Body force
ϑ	Kinematic viscosity

REFERENCES

[1] https://www.rainfordsolutions.com/ip65-or-ip66-ip-ratings-explained
[2] https://www.inverterdrivesystems.com/what-is-an-inverter/
[3] A. Bar-Cohen, W. M. Rohsenow Thermally Optimum Spacing of Vertical, Natural Convection Cooled, Parallel Plates, in: Journal of Heat Transfer, Vol 106, p. 116-123, 1984
[4] R.K. Rajput, Heat and Mass Transfer, 3rd ed, S.Chand, New Delhi, 2006, pp. 352-372, pp. 495-527
[5] Senapati, J.R., Dash, S.K. and Roy, S., 2016. Numerical investigation of natural convection heat transfer over annular finned horizontal cylinder. International Journal of Heat and Mass Transfer, 96, pp.330- 345
[6] R Simons, Simplified Formula for Estimating Natural Convection Heat Transfer Coefficient on a Flat Plate, in: Electronics Cooling, Issue: August 2001
[7] Stehouwer, H.P. and Hertog, D. den, Simulation-Based Design Optimization: Methodology and Applications, Proceedings of the First ASMO UK / ISSMO Conference on Engineering Design Optimization, Ilkley, UK, 1999.
[8] Parry, J., Bornoff, R., Stehouwer, H.P., Driessen L.T., and Stinstra, E.D., Simulation-Based Design Optimization Methodologies Applied to CFD, Proceedings SEMITHERM XIX, San Jose, 2003, pp. 8-13