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Thermal management of PQ transformer for a passively cooled power module

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Abstract**—** In this paper we study the thermal performance of a 5 kW rectifier module experimentally and numerically, with the aim of changing the cooling methodology from an active cooled (fan cooled) to a passively cooled system. Numerical model of the rectifier for fan cooled operation is developed and experimentally validated, following which the critical components in the system are identified. In this system, magnetic components like transformers were observed to have the poorest thermal performance. Given the lack of attention thermal management of magnetic components has received compared to switching components, we numerically study the thermal performance of a PQ 40/40 transformer in a passive (natural convection) scenario. Modifications to the transformer structure were studied and the heat transfer from the transformer was observed to be convection limited (large convection thermal resistance). Providing a minimum resistance conduction path from effective hot spot to ambient was observed to be the best practice. Further, providing a heat transfer path between the coil and core was observed to be crucial to transformer thermal performance.

Keywords - thermal management; CFD; passive cooling; PQ 40/40 transformer;

I. INTRODUCTION

Power electronic systems play a vital role in telecommunication, aerospace and various other industries. Modern day power electronic systems generally run at high efficiencies due to the application of innovative conversion topologies. Despite this, a significant amount of heat is dissipated, especially for high power rated electronic systems.

The need for thermal management of electronic systems has been accentuated by both the tendency of components to fail at elevated temperatures and the trend of miniaturization of transistors in switching devices over the years. This is evidenced by the Arrhenius law [1], which states that device failure rates increase exponentially with operating temperature and by Moore's Law which states that the number of transistors in Integrated Circuits (ICs) approximately doubles every two years [2] respectively. This miniaturization of switching components has led to increased heat fluxes due to reduction of area available for heat transfer and increase in power dissipation. Modern day semiconductors are reported to dissipate around 1-100 W/cm^2 of heat [3].

Active cooling methods like fan cooling are the most commonly used cooling methodology for such electronic systems. Although this is a simple method and can handle thermal loads up to 0.04 W/cm^2 [4], it faces some drawbacks. Fan cooled systems generally consume parasitic power [5] and have low reliability. Further, fans produce a lot of noise and cannot be implemented in locations with strict acoustic regulations. The reliability and robustness offered by passive cooling systems has drawn attention, especially in the renewable energy sector for outdoor applications where access for maintenance is limited.

Irrespective of the cooling methodology, providing a system/module level cooling solution would require understanding of component level heat transfer before a foray is made into providing a system level cooling modification. The heat transfer characteristics of switching components like IC's and MOSFETS have been extensively studied by numerous authors [6]-[7] and the thermal bottlenecks have been identified. Magnetic components in such systems has received less attention. Biela and Kolar *et al.* [8] studied thermal performance of a transformer using a heat transfer component as an insert, Pavlovsky *et al.* [9] similarly used a conduction based methodology using a heat pipe for heat removal from hot spot. Apart from a few studies, most studies on transformer thermal management are limited to large scale oil cooled power transformers [10]-[11].

This study evaluates the thermal management of conventional PQ 40/40 transformers used in power conversion systems to achieve passive cooling.

II. PROBLEM DEFINITION

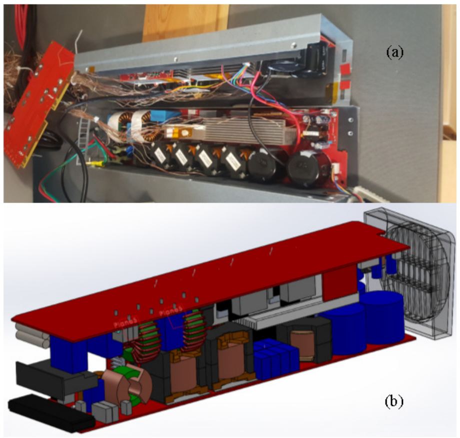

Figure 1. (a) Unbolted module under study. (b) CAD model of the module without chassis to highlight internal details

The objective of our research is to redesign a power module as shown in Fig. 1(a) from an active (fan cooled) to a purely passive design. The system in question is a 5 kW rated rectifier power module operating at 240 V AC input and providing 54 V DC output. The internal geometry of the power module can be visualized in Fig. 1(b) while the unbolted view of the module can be seen in Fig. 1(a).

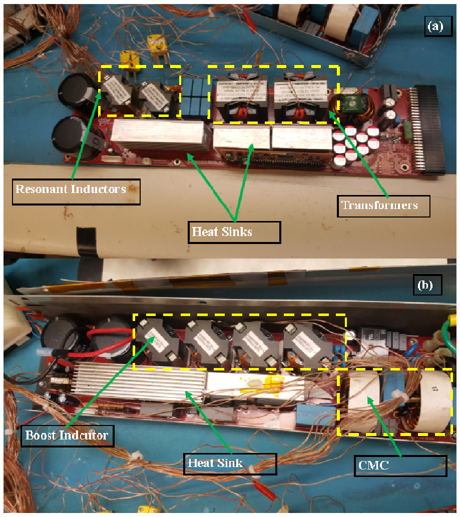

Figure 2. (a) DC-DC converter. (b) PFC converter

This power rectifier module utilizes two distinct topologies, the Power Factor Correction (PFC) converter and the DC-DC converter. The PFC converter provides a modulated signal to the DC-DC converter, which in turn provides the required DC output. The major heat dissipating components on the DC-DC side and PFC side can be seen in Fig. 2(a) and Fig. 2(b) respectively, with the switching components being mounted on the heat sinks

The two converters constituting the power conversion system are fixed facing each other as seen in Fig. 1 (b) with the PFC side on the top and DC-DC on the bottom. The system runs at an efficiency of 95.7 % at full load and dissipates around 202 W. This configuration has been designed for fan cooling, using a 12 VDC rated Delta model AFB0712SHCCM fan.

Now, to realize passive cooling of such a design, we follow the research methodology as described in Fig. 3.

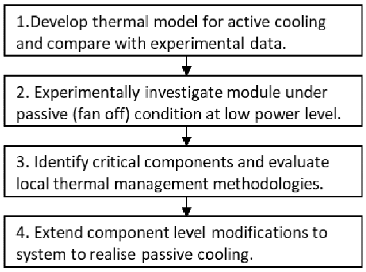

Figure 3: Research Methodology

The first step of our study is to develop a computational model for the current (fan cooled) operation of the system/module and compare with numerical results. This is to help validate our modelling methodology.

Once we have established confidence in our modeling methodology, the module is tested with its fan off at a low power level. This would help us characterize the challenge of passive cooling for such a design and help identify the critical components. Once the critical components are identified, the best practice is to study these components in isolation instead of analyzing their thermal performance in a system/module analysis, Further, if we can locally manage the heat being dissipated from these critical components, the system level thermal managment is greatly simplified and the local themal management methodology can be extended to the sytem level thermal mangement concept.

III. EXPERIMENTAL SETUP

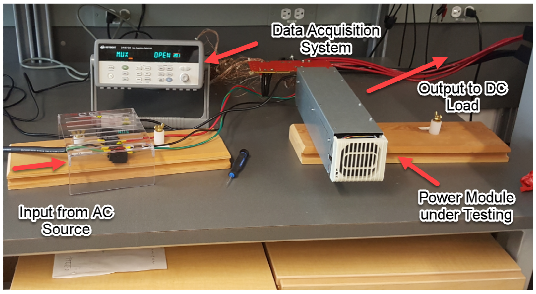

Figure 4: Experimental Setup for module under testing.

The experimental setup can be visualized in Fig. 4. Chroma model 6460 programmable AC source was used to provide a 240V AC input to the unit under testing while a Chroma model 63204 DC electronic load was used as the output. The thermal performance of the module was evaluated by attaching K type thermocouples to components that dissipate heat. Keystone model 34970A data acquisition system was used to connect to the thermocouples for datalogging.

The fan cooled experimental analysis of the module was run until the temperature variation was less than 2 °C within one hour, which was considered as steady state. In this condition the module was run at multiple power levels. The passive (no fan) thermal testing on the other hand was done at a low power level of 0.5 kW (10% full load) as the module is designed for active (fan) cooling and the thermal performance can be expected to be poor. Further, the real time thermocouple data was closely monitored and the system was shut off when component temperatures were close to their safe operating threshold temperature.

IV. NUMERICAL ANALYSIS

This section discusses the numerical methodology followed by this study. This section will be divided into two parts. The first discusses the analysis methodology for active cooling (with fan) of the module (system level simulation) while the other discusses the analysis methodology of an isolated PQ 40/40 transformer (component level) in a natural convection scenario. All simulation results are for steady state.

A. Active Cooling of Power Module

The computational domain under study can be seen in Fig. 5. The numerical modelling and simulation is carried out using commercially available CFD software ANSYS Icepack. The dimensions of the domain are 0.08 m, 0.07596 m, 0.37935 m in the *x*, *y* and *z* direction respectively. The module is enclosed by an aluminum chassis. The fan can be seen in Fig. 5 and the flow rate depends on the fan curve, which is provided as an input to the solver. The other face highlighted in dark blue in Fig. 5 is open to the ambient.

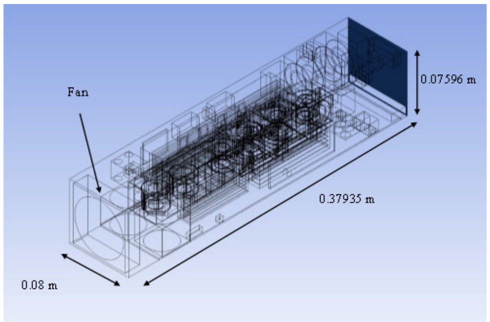

Figure 5: Active cooling computational domain, face open to ambient is highlighted in dark blue.

Convective boundary condition of 5 $W/m^2\cdot K$ is applied to the external walls of the chassis, while the outlet (highlighted in Fig. 5) is open to ambient pressure (1 atm) and temperature (22 °C). RNG *k*-ε turbulence model is used to model the turbulent nature of the flow. No slip boundary condition is applied at solid-fluid interfaces.

A control volume method was used to discretize the domain and a semi-implicit method for pressure linked equation (SIMPLE) method was used for pressure-velocity coupling. The discrete algebraic equations are solved by a point implicit (Gauss Seidel) method in conjugation with an Algebraic Multigrid (AMG) method. This helps reduce the computational time required for each simulation. The conservation equations being solved for are (1), (2) and (3) in the fluid domain and (3) in the solid domain (reduces to simple conduction equation).

$$\frac{\partial\rho}{\partial t}+\nabla(\rho\vec{v})=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla(\rho\vec{v}\vec{v})=-\nabla P+\nabla(\bar{\bar{\tau}})+\rho\vec{g}+\vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h)+\nabla(\rho h\vec{v})=\nabla[(k+k_t)\nabla T]+S_h \tag{3}$$

Here, ρ is density, $\vec{v}$ is velocity vector, P is pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\vec{F}$ is the source term, h is enthalpy, k is the molecular thermal conductivity, k_t is the conductivity due to turbulent transport, T is temperature and S_h is the source term like volumetric heat generation.

The convergence criteria is fixed at 10^{-4} for velocity and 10^{-7} for energy. As for the mesh, unstructured tetrahedral cells are generated by in house meshing software Mesher-HD. The mesh density is higher near the surface of solids to ensure resolution of boundary layer. The total mesh count is around 6531290 cells.

B. Isolated PQ 40/40 transformer

The computational domain used for this analysis can be seen in Fig. 6. The dimensions are 0.088 m, 0.053616 m, 0.2 m in the *x*, *y* and *z* directions respectively. The dimensions of the transformer itself can be readily found in manufacturer datasheets [12]. The transformer is mounted on a PCB (highlighted in yellow) and enclosed in an aluminum chassis. The domain is set such that it is representative of the small form factor characteristic of such problems.

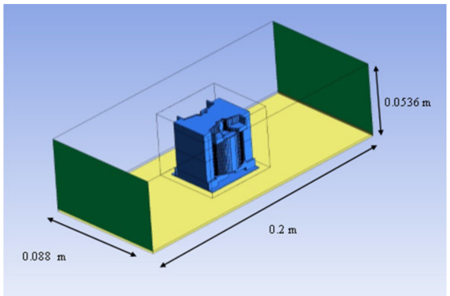

Figure 6: Computational domain for isolated PQ transformer under study, faces open to ambient highlighted in green.

A convective boundary condition of 5 $W/m^2\cdot K$ is applied to the external walls of the chassis. The other two faces, as highlighted in green, are open to ambient. One of the key assumptions made in modelling such a transformer, is that the windings are approximated/modelled as a foil.

The same conservation equations and solvers have been used as the previous active cooling analysis. The only change is that, in this case the flow is entirely laminar and no turbulence model is employed. But to characterize natural convection, the Bossinesq approximation is used. The convergence criteria is again set as 10^{-4} for velocity and 10^{-7} for energy. The mesh element count is around 1841815 cells.

V. RESULTS

The organization of this section will follow the research methodology as described in Fig. 3.

A. *Active cooling: experimental vs numerical*

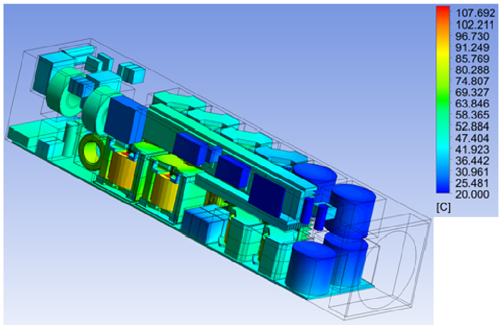

Figure 7: Temperature contour for active (fan cooled) operation of power module at 4.5 kW. The thermal contours of the top PCB is not shown.

The experimental and numerical test was run for multiple power levels. Fig. 7 shows the global temperature contours for the module at a power level of 4.5 kW. Table. 1 shows the comparison between the experimental and numerical results at 4.5 kW. The model can predict temperature within 10-15% of its experimental values. The results for other power levels were excluded for the sake of brevity. Given the complexity of the problem, we were satisfied with our modelling methodology and progressed to the next step of the analysis.

Table 1: Comparison of experimental vs numerical results for a few components at 4.5 kW for active cooling condition.

Component	Experimental (°C)	Numerical (°C)	Error
Transformer winding inside (1st)	112	107	-4.46
Transformer Core	56	53	-5.35
Primary MOSFET	50	55	10
Secondary MOSFET	57	62	8.77
Resonant inductor inside	93	85	-8.6
Resonant capacitor	44	40	-9

B. *Experimental passive cooling (0.5 kW)*

Fig. 8 shows the temperature versus time plot for passive (fan off) testing of the module at 0.5 kW. From Fig. 8 we can see that the curve has not yet reached steady state as the test was shut off as specified in the previous sections. The components with the poorest thermal performance are the transformers and the MOSFETs on the DC-DC side. The components on the PFC side of the rectifier show relatively good thermal performance. The temperature within the primary windings of the first transformer (first from the end open to ambient) is the global hot spot in this system. Given the slope of the curve we can assume that the system would have failed if run for longer. The test is clearly indictive of the transformer being the most critical component in this system.

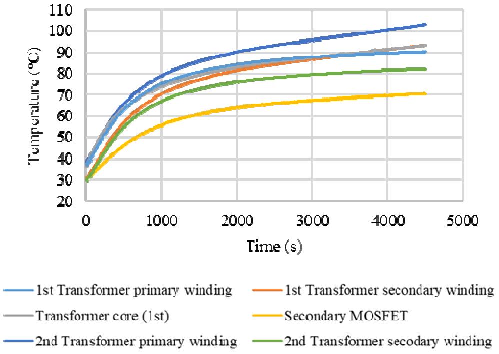

Figure 8: Thermocouple data for fan off testing condition at 0.5 kW. Only critical components are shown.

C. *Isolated PQ 40/40 transfomer (Component Level)*

Now that we have established that the transformer is the most critical component in a passive (fan off scenario). We study the results of our component level thermal analysis.

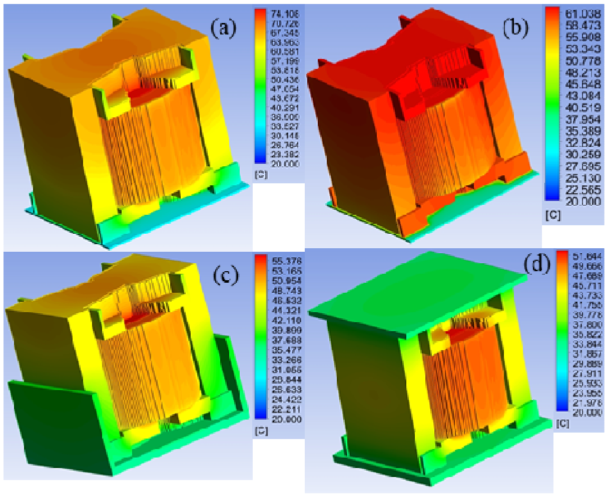

Figure 9. (a) Thermal contour of conventional PQ transformer (5 W loss). (b) Thermal contour of transformer with internal modification. (c) Thermal contour of transformer with external modification 1 (U clamp). (d) Thermal contour of transformer with external modification 2 (double sided cooling).

Fig. 9(a) shows the thermal contour of a conventional PQ 40/40 transformer dissipating a total of 5 W (4 W copper loss and 1 W iron loss). We can observe that the hot spot is predicted to be inside the primary winding. Further we observe a large temperature gradient between the internal structure of the transformer and the core side leg. This is indicative of a large internal thermal resistance.

Now, let us highlight the modifications and their corresponding effects on thermal performance.

1) *Internal Modification :* Change of bobbin material from thermosetting plastic to Ceramic (ALN).

The role of bobbin in a transformer is to provide mechanical support to the winding structure whilst also providing electrical insulation. Bobbins are generally made from plastics like Polytetrafluoroethylene (PTFE) which are characteristic of a low thermal conductivity (k~0.25 W/m·K). Ceramic materials like Aluminum Nitride (ALN) has similar electrical insulating characteristics as plastics (insulation of around 15 kV/mm), while possessing superior thermal characteristics (k~150 W/mK). The first modification we study is changing the bobbin material from plastic (PTFE) to ALN. Fig. 9 (b) shows the temperature contour for this modification, we can see that heat spreading is greatly improved and the transformer almost behaves like a lumped thermal mass. The hot spot is also reduced by around 13 °C. An interesting property of ferrite cores (3C96 in this case) is lower iron loss and better thermal performance at elevated temperatures (around 100 °C). Hence, providing a heat transfer path between the core and windings is beneficial not just to thermal performance but also the magnetic performance of the core.

2) External Modification 1 : U clamp made of ceramic, bonded to the bottom of the transformer to provide a conduction path to the chassis of the module. The PCB layer is cut through to provide a direct path to the chassis

Liu *et al.* [13] observed that providing ceramic inserts within the ferrite core is beneficial to heat transfer in a natural conduction scenario. We similarly extended this finding to our case by bonding a U-clamp (base plate: 0.038 m*0.0445 m*0.002m, side legs: 0.038 m*0.021076 m*0.001 m) to the bottom of the transformer and connecting it directly to the chassis by cutting through the PCB layer. The thermal benefit of such a modification can be seen in Fig. 9(c), we can observe a reduction in hot spot temperature of around 20 °C. Due to the small factor characteristic of such transformers and low heat transfer coefficient (HTC) in natural convection scenario (around 10 $W/m^2 \cdot K$ for the core side leg,) the convective resistance to air within the module is very high and providing a purely conductive heat transfer path to the ambient is greatly beneficial to heat transfer.

3) External Modification 2: Double sided cooling to provide a conduction path from the transfomer to the chassis on both top and bottom sides.

In this modification, we provide a ceramic interface (0.038 m*0.0445 m*2 m) between both the bottom and top surface of the transformer and the chassis. Generally, most electronic packaging methodologies have a large air gap between the components and the top of the chassis. This air gap is not very beneficial to heat transfer in a natural convection scenario (low HTC, around 5 $W/m^2 \cdot K$). We circumvent this by directly bonding it the top of the transformer to a ceramic interface. This modification provides a conduction path to the ambient in two directions. The benefit of this modification can be seen in Fig. 9 (d), with a reduction in hot spot temperature of around 24 °C. This holds good with our finding that the heat transfer for a PQ transformer in a natural convection scenario is convection limited and providing a minimum resistance conduction path to the ambient is the best practice for thermal management.

Although the modifications we study are an ideal case, as there is no conjugate heat transfer between different components and there is a large dedicated chassis area for heat dissipation to ambient, we can clearly see that providing a minimum resistance path from the transformer to the chassis is the best thermal management practice to realize passive cooling.

CONCLUSION

In this study, experimental and numerical analysis was carried out for a 5 kW rectifier power module. Critical components in this system were identified to be magnetic components like transformers. Numerical model for the fan cooled operation was validated with experimental results. Further, numerical model of a PQ 40/40 transformer was developed and studied from a passive cooling point of view. The heat transfer was observed to be convection limited and providing a minimum resistance conduction path to ambient was observed to be the best practice to realize passive cooling. Modifications of the bobbin material was also studied and the importance of providing a heat transfer path between the core and coil was observed to be beneficial for both heat transfer and general operation of the core. The effect of these changes is yet to be evaluated experimentally.

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